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Hu et al.

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(45) Date of Patent: Jun. 23, 2015

(54) BALUNS, A FINE BALANCE AND IMPEDANCE ADJUSTMENT MODULE, A MULTI-LAYER TRANSMISSION LINE, AND TRANSMISSION LINE NMR PROBES USING SAME

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1128 days.

(21) Appl. No.: **13/065,446**

(22) Filed: **Mar. 22, 2011**

(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation of application No. 12/313,385, filed on Nov. 20, 2008, now Pat. No. 7,936,171.

(60) Provisional application No. 60/989,494, filed on Nov. 21, 2007.

(51) **Int. Cl.**
H01P 5/02 (2006.01)
H01P 5/10 (2006.01)

(52) **U.S. Cl.**
CPC ... ***H01P 5/02*** (2013.01); ***H01P 5/10*** (2013.01)

(58) **Field of Classification Search**
CPC G01R 33/34046; H01P 5/02; H01P 5/10
USPC 324/300–322; 600/409–445
See application file for complete search history.

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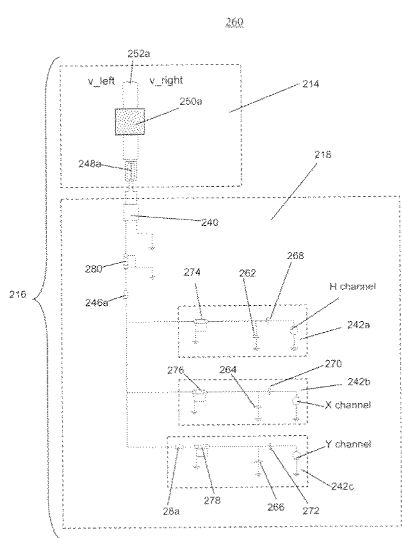
Primary Examiner — Dixomara Vargas
(74) *Attorney, Agent, or Firm* — Iandiorio Teska & Coleman, LLP

(57) **ABSTRACT**

A pseudo-Marchand balun, compound balun and tunable multi-resonant coaxial balun, and NMR probes employing each such balun, and a fine balance and impedance adjustment module and a multi-layer transmission line for use in such NMR probes.

7 Claims, 26 Drawing Sheets



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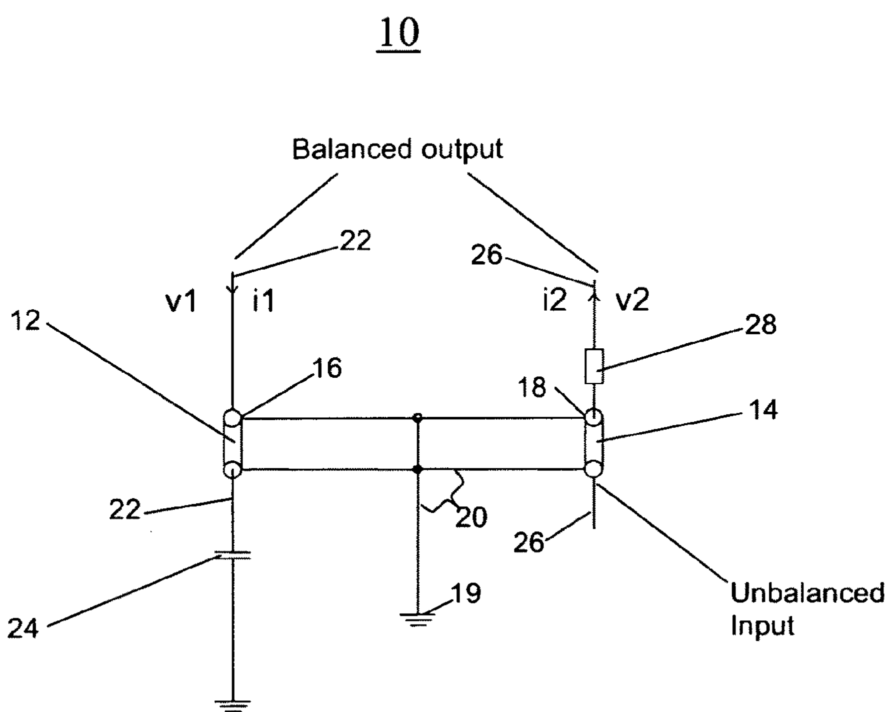

10
Balanced output
22
26
v1
i1
i2
v2
12
28
16
18
14
22
20
26
19
24
Unbalanced
Input

FIG. 1

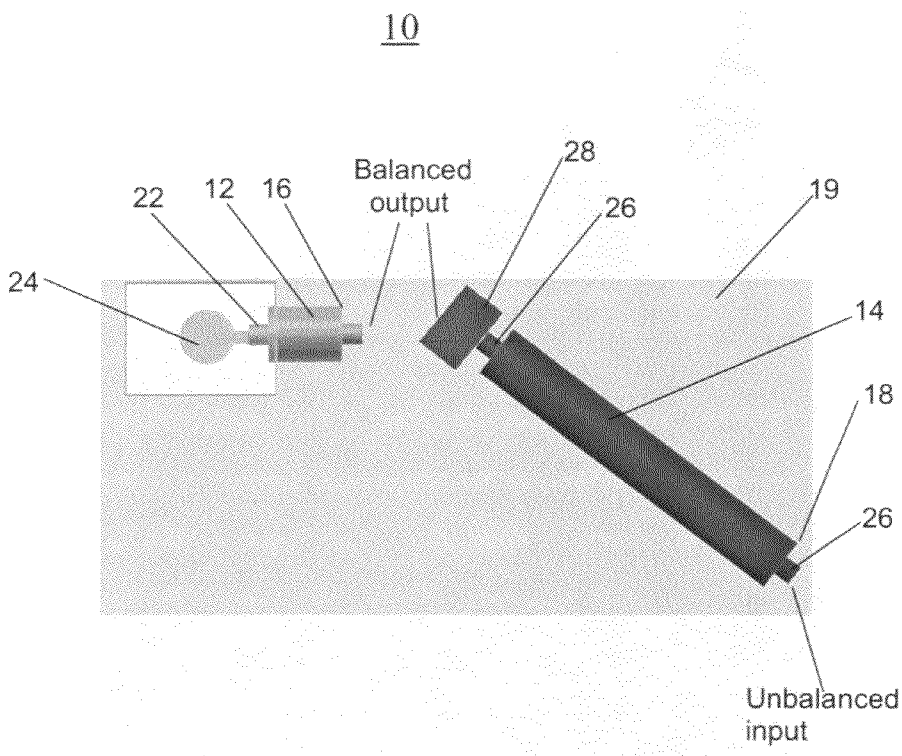

10
28
Balanced
output
26
19
22
12
16
24
14
18
26
Unbalanced
input

FIG. 2

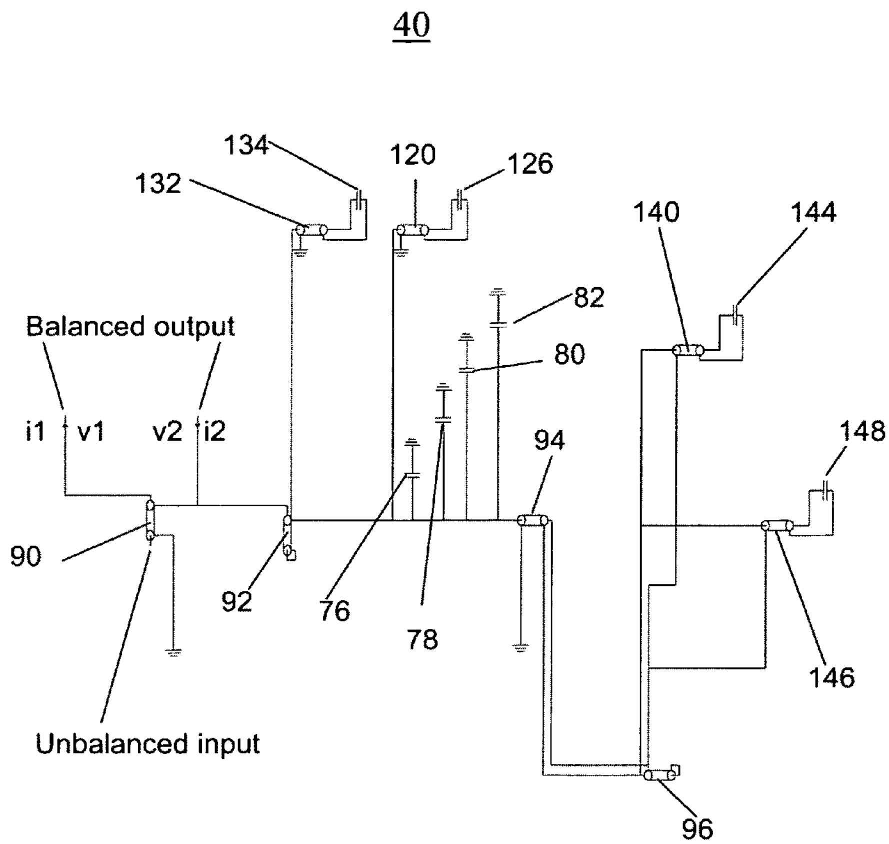
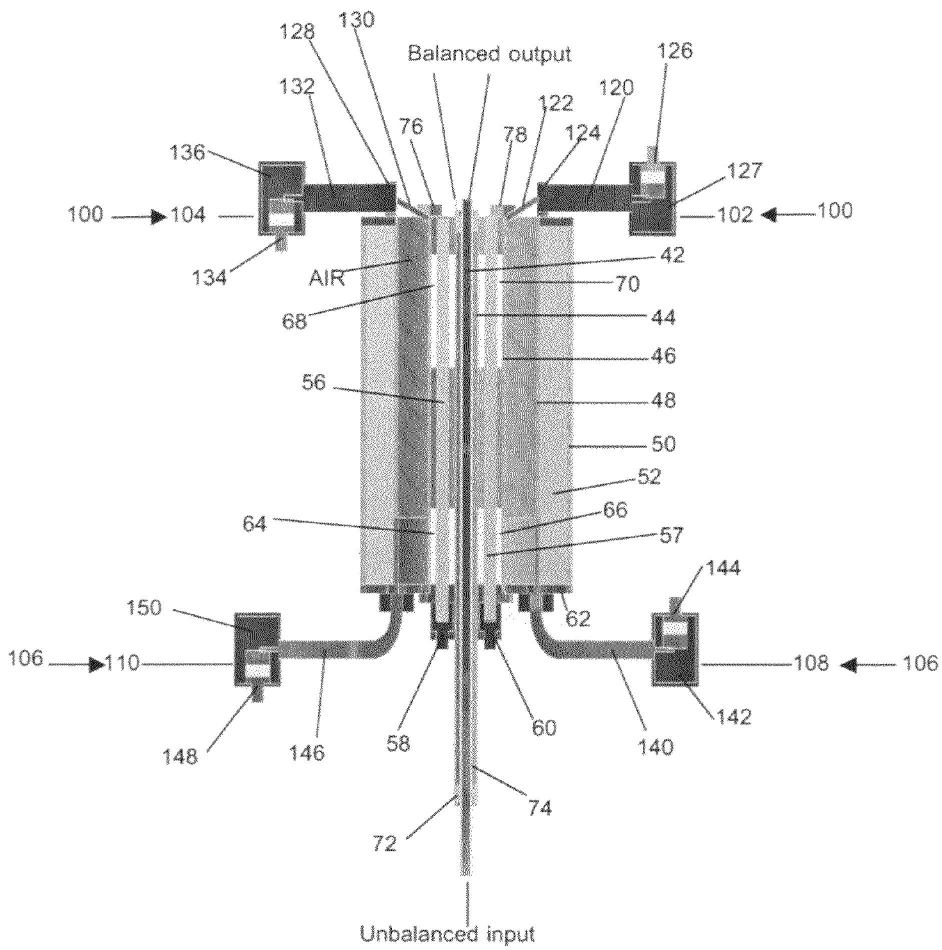

40
134
120
126
132
140
144
82
Balanced output
80
i1
v1
v2
i2
94
148
90
92
76
78
146
Unbalanced input
96

FIG. 3

40



128
130
Balanced output
126
132
122
120
76
78
124
136
127
100
104
102
100
134
AIR
42
70
68
44
46
56
48
50
52
64
66
57
144
150
62
106
110
108
106
142
148
146
58
60
140
74
72
Unbalanced input

FIG. 4

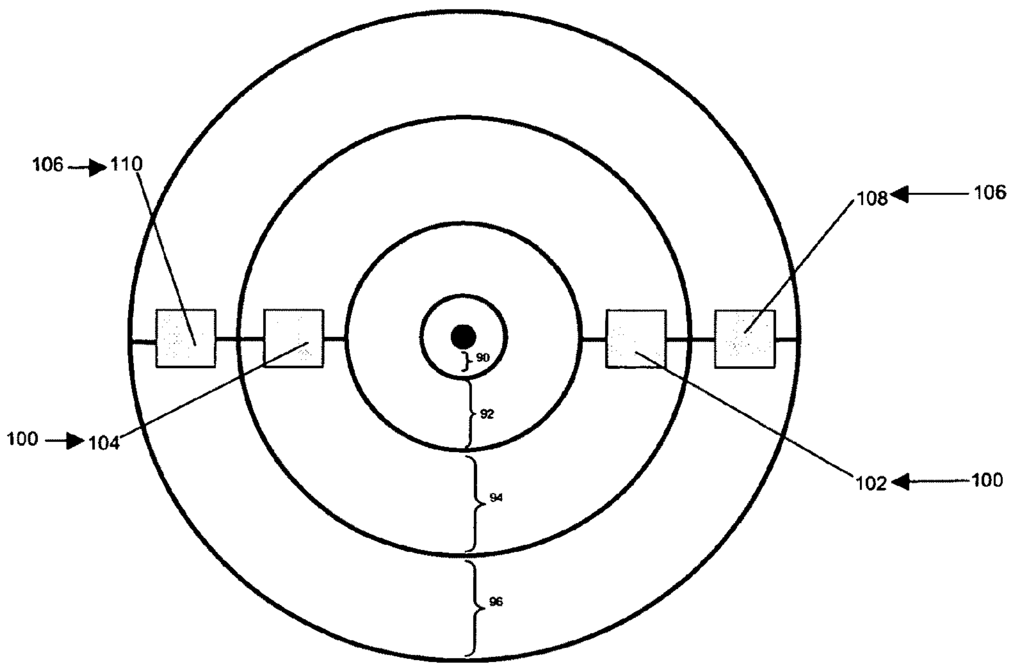


FIG. 4A

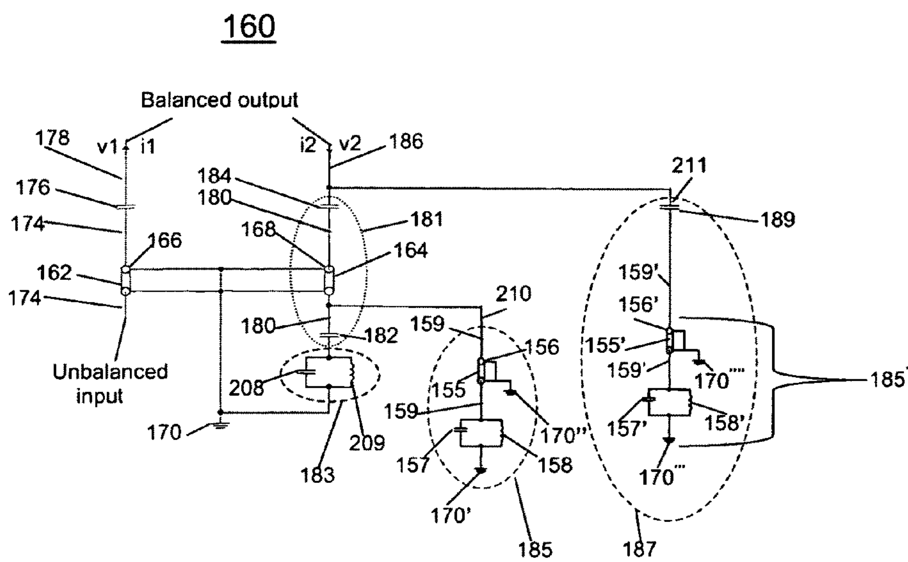

160
Balanced output
178
v1
i1
i2
v2
186
176
174
184
180
181
168
166
164
162
174
180
182
Unbalanced input
208
209
183
170
210
159
156
155
159
157
158
170''
170'
185
211
189
159'
156'
155'
159'
170''''
157'
158'
170'''
185'
187

FIG. 5

160

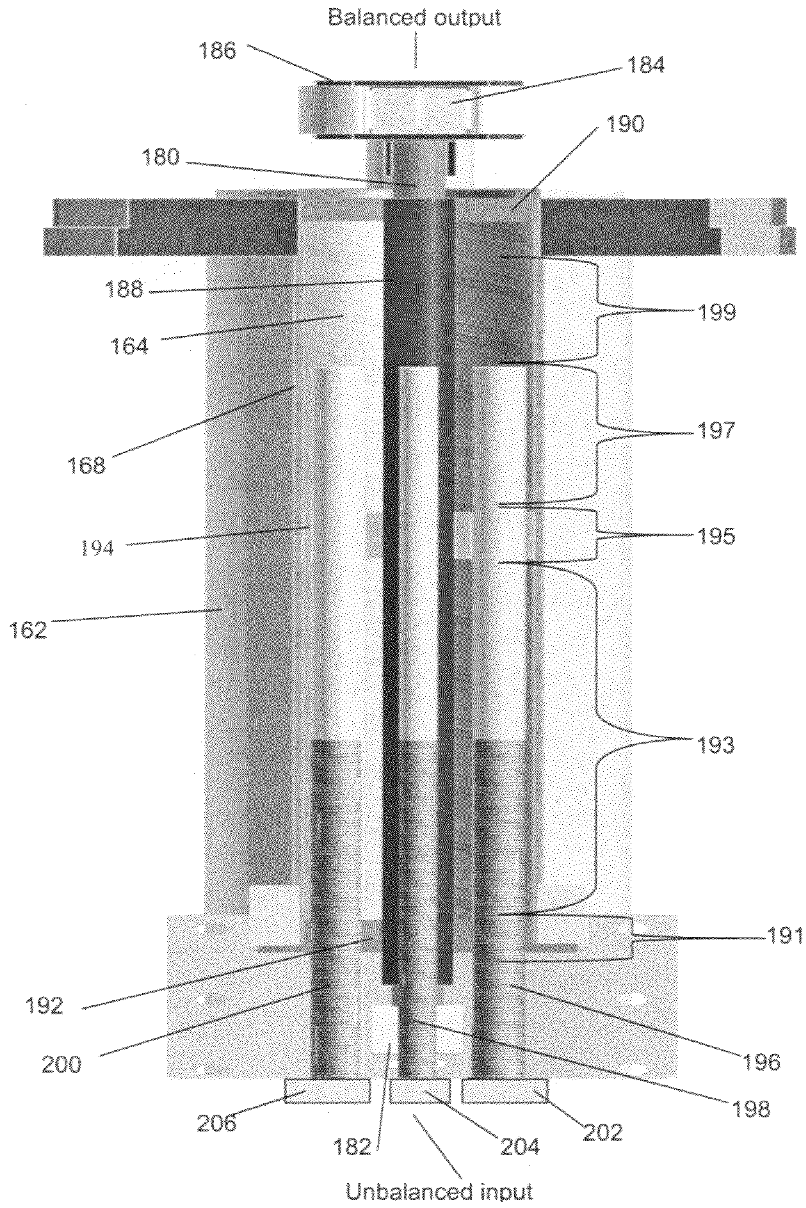

Balanced output
186
184
190
180
188
199
164
197
168
195
194
162
193
191
192
200
196
198
206
182
204
202
Unbalanced input

FIG. 6

210

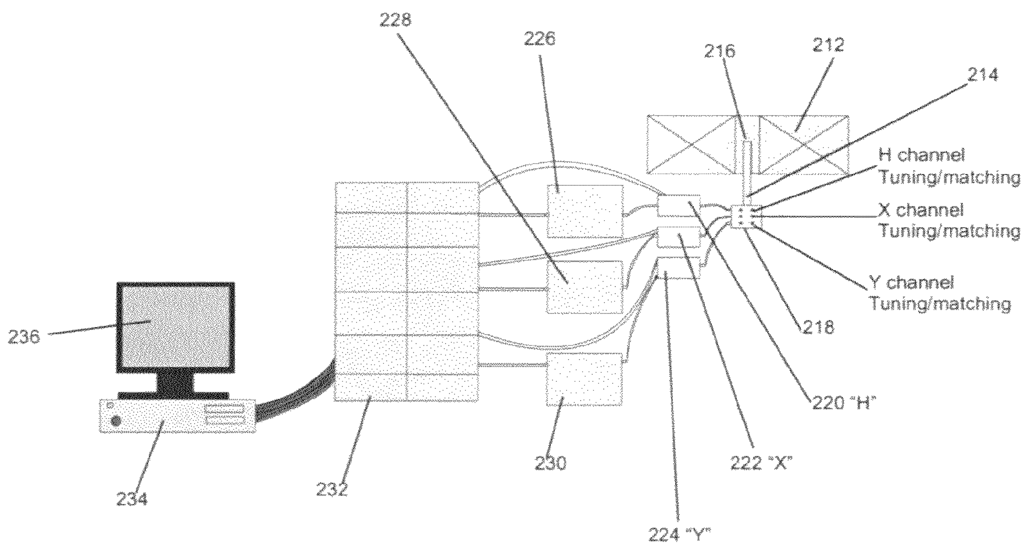

228
226
216
212
214
H channel
Tuning/matching
X channel
Tuning/matching
Y channel
Tuning/matching
236
218
220 "H"
222 "X"
230
224 "Y"
234
232

FIG. 7

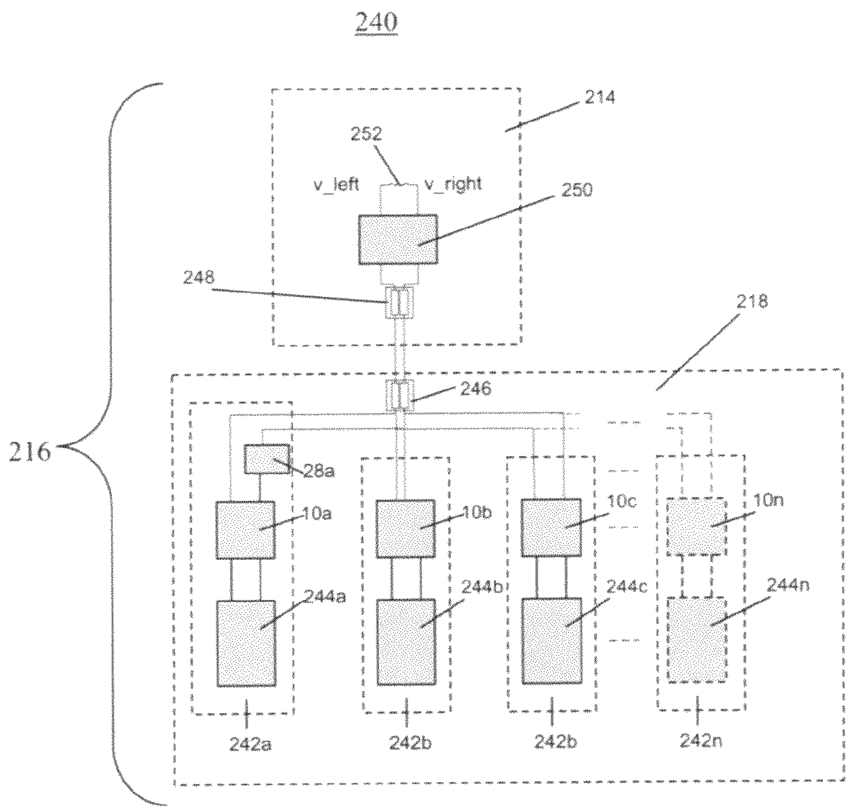

240
214
252
v_left
v_right
250
248
218
246
216
28a
10a
10b
10c
10n
244a
244b
244c
244n
242a
242b
242b
242n

FIG. 8

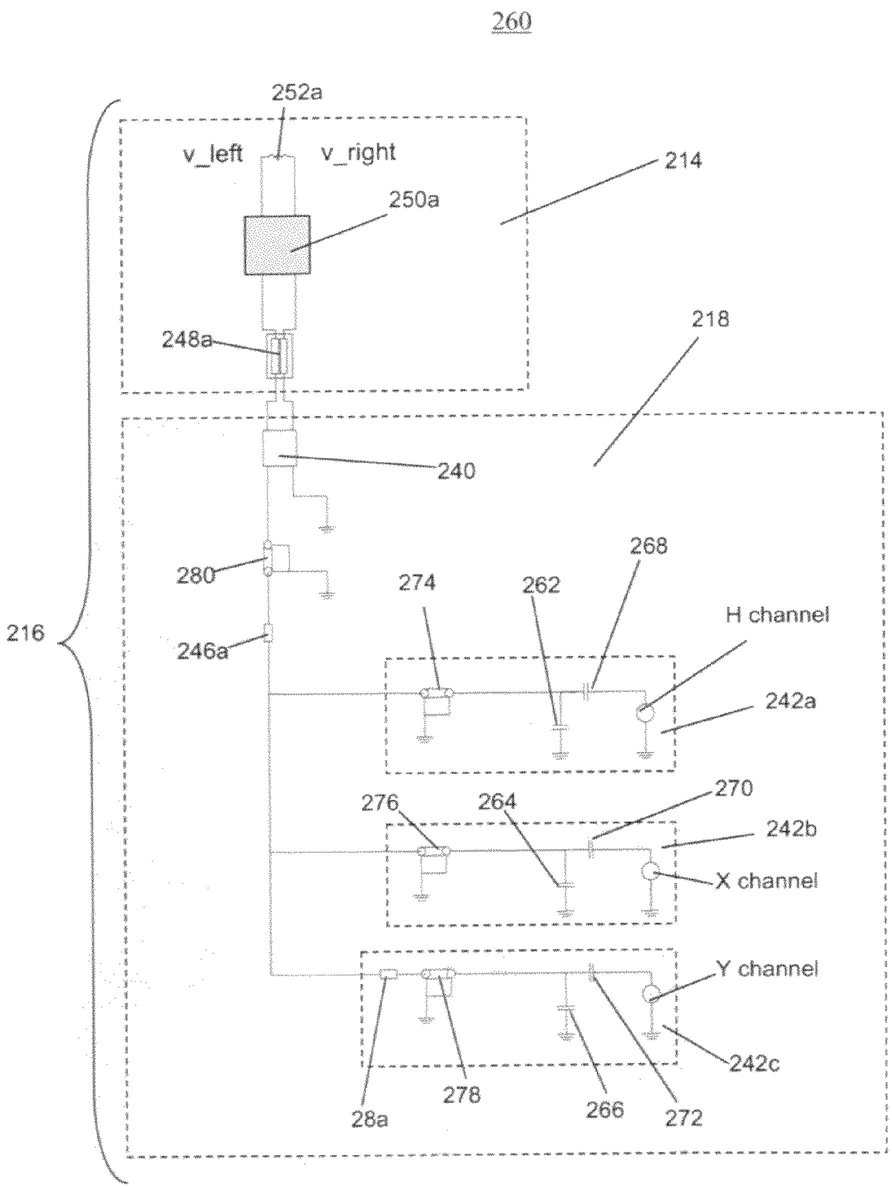

260
252a
v_left
v_right
214
250a
218
248a
240
268
280
274
262
H channel
216
246a
242a
276
264
270
242b
X channel
Y channel
242c
28a
278
266
272

FIG. 9

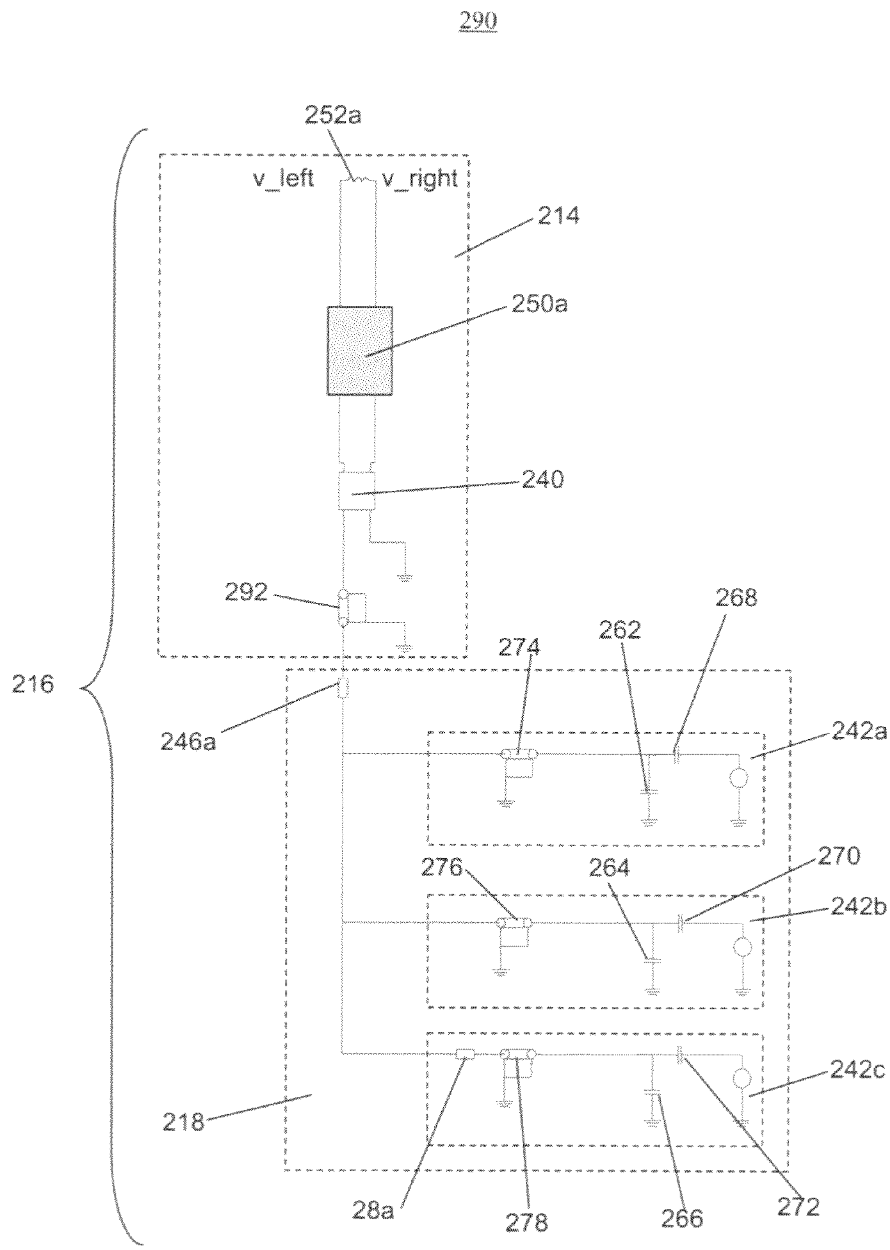
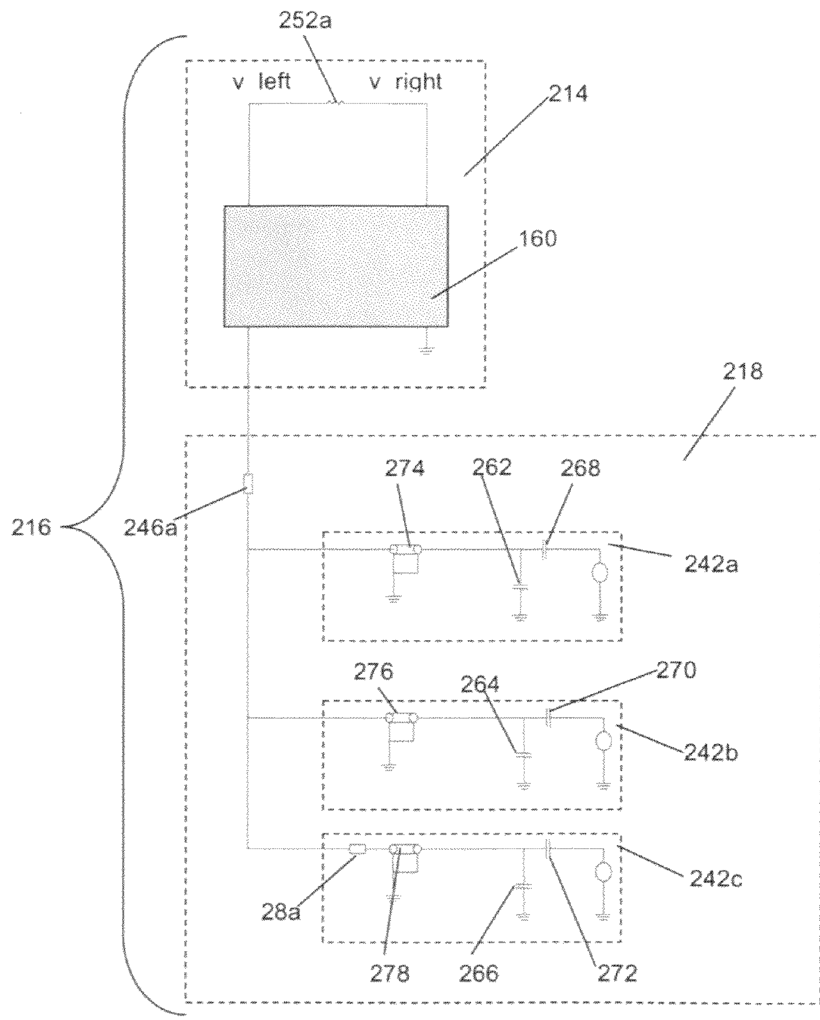

290
252a
v_left
v_right
214
250a
240
292
274
262
268
216
246a
242a
276
264
270
242b
242c
218
28a
278
266
272

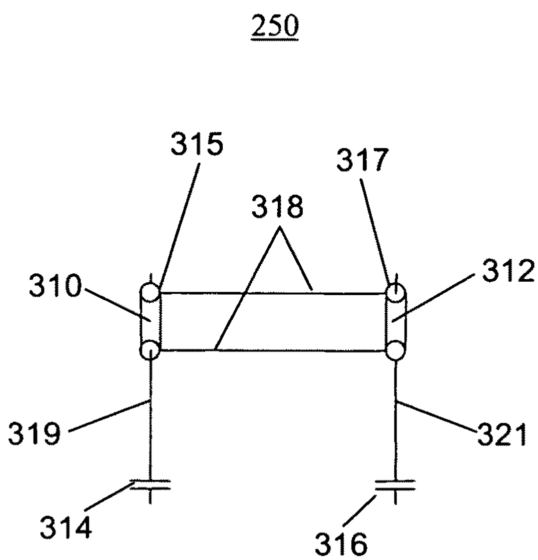
FIG. 10

300



252a
v left
v right
214
160
218
274
262
268
216
246a
242a
276
264
270
242b
242c
28a
278
266
272

FIG. 11



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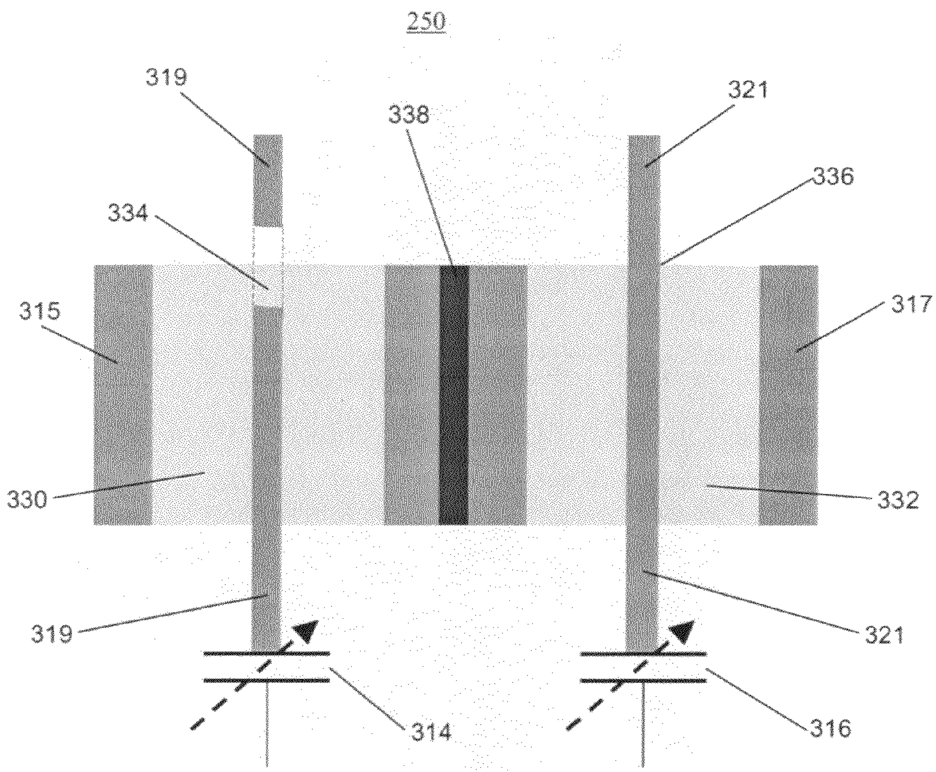

FIG. 13

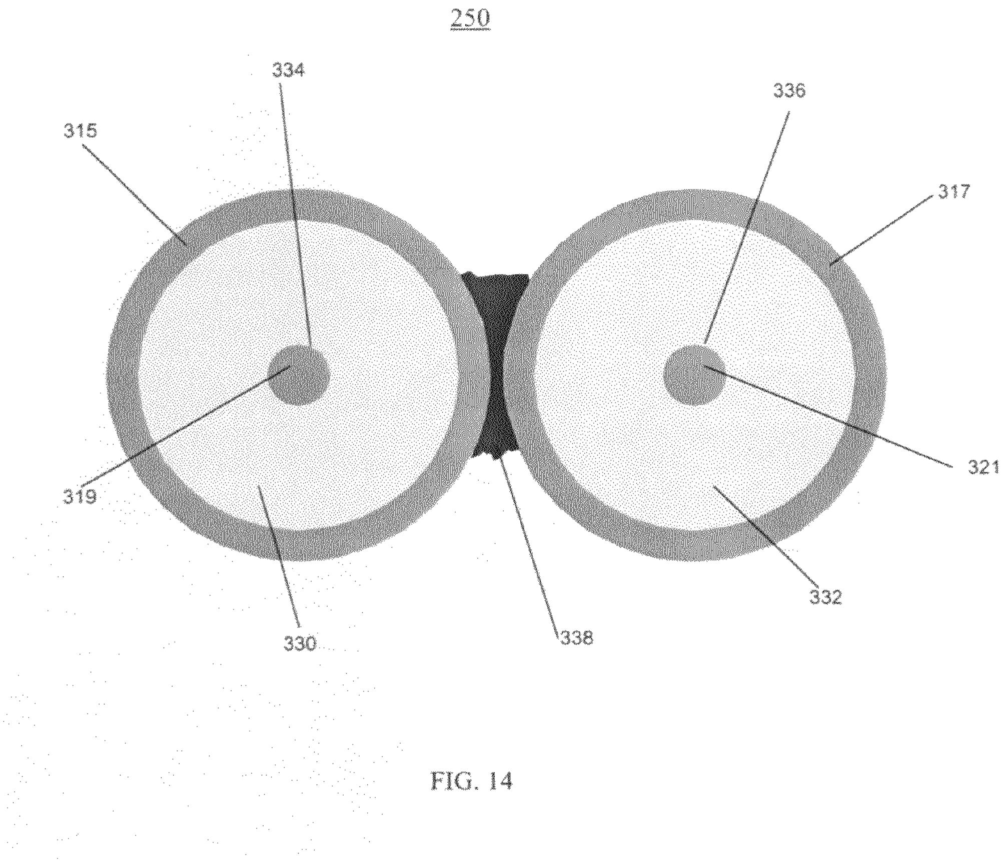

FIG. 14

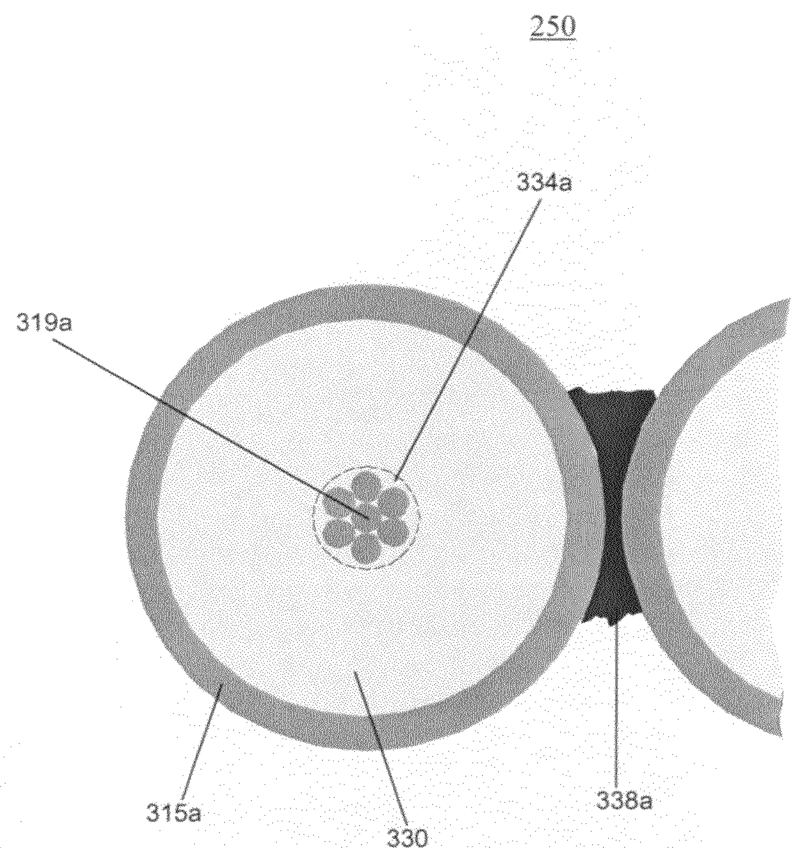

FIG. 15

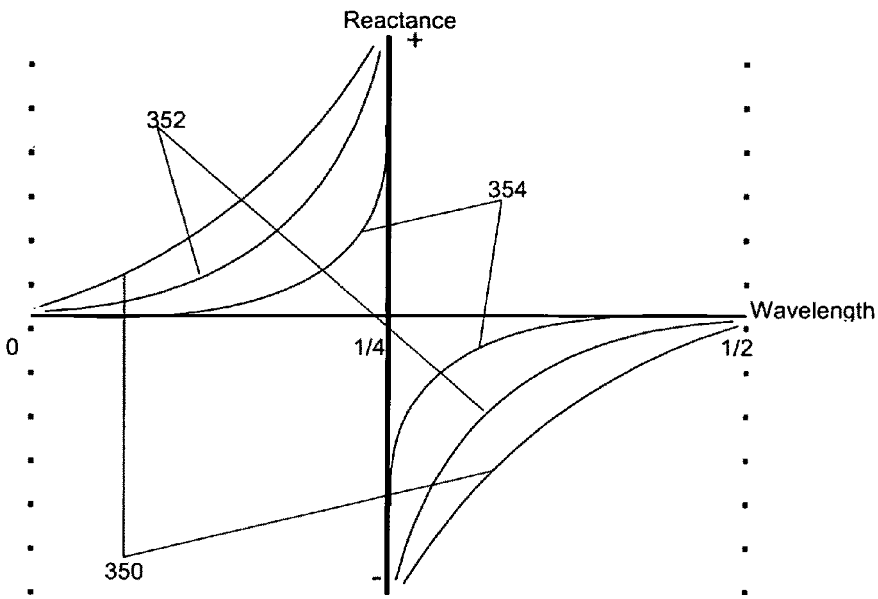

FIG. 16
PRIOR ART

248’

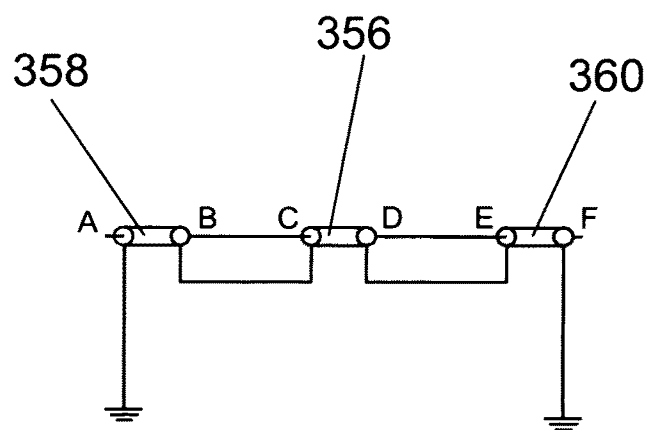

FIG. 17

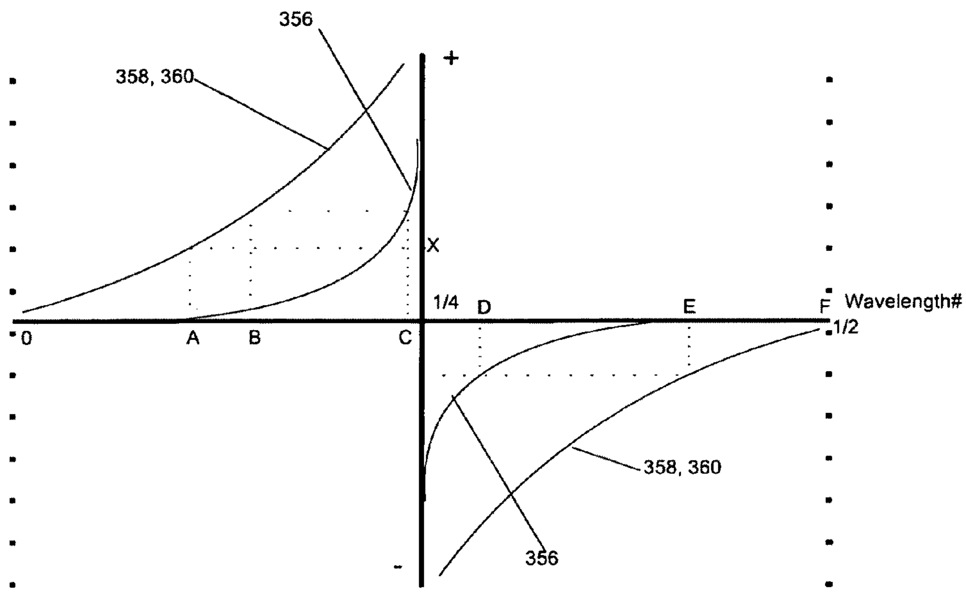

FIG. 18

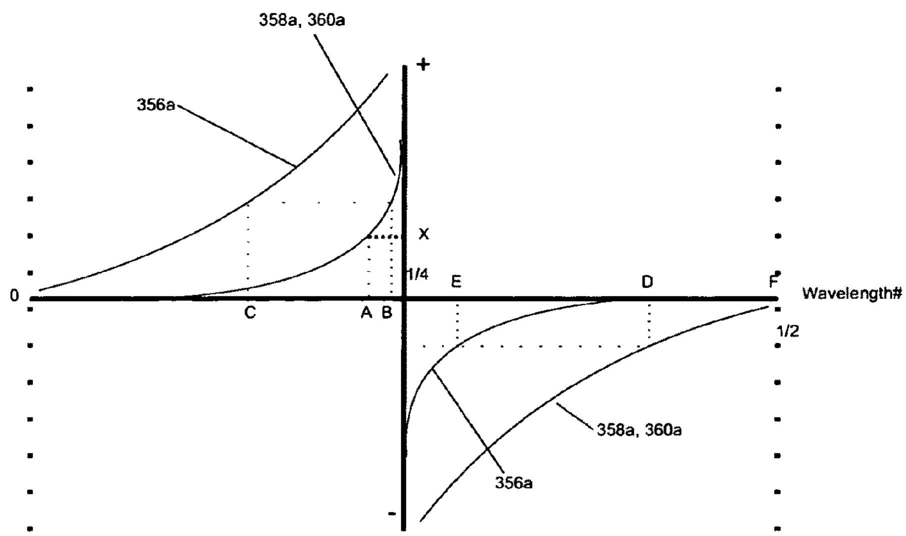

FIG. 19

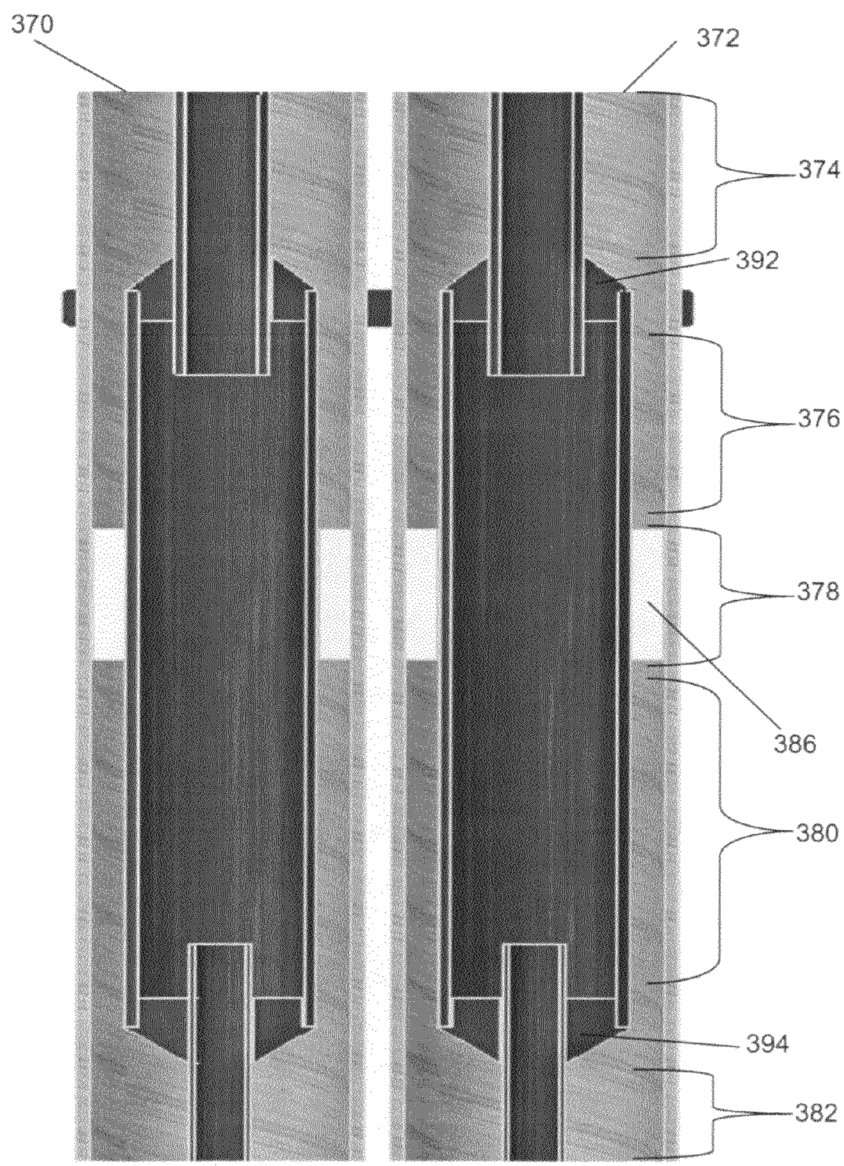

FIG. 20

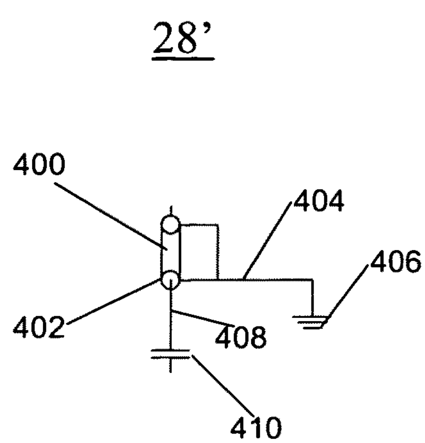

FIG.21

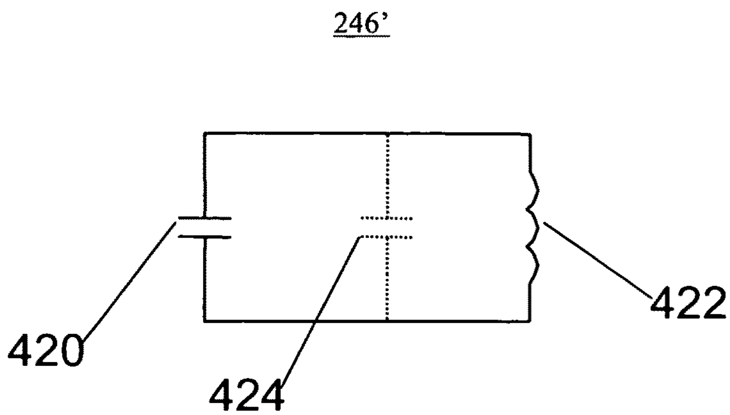

FIG. 22

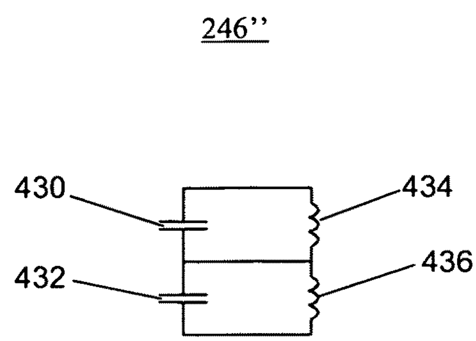

FIG. 23

246'''

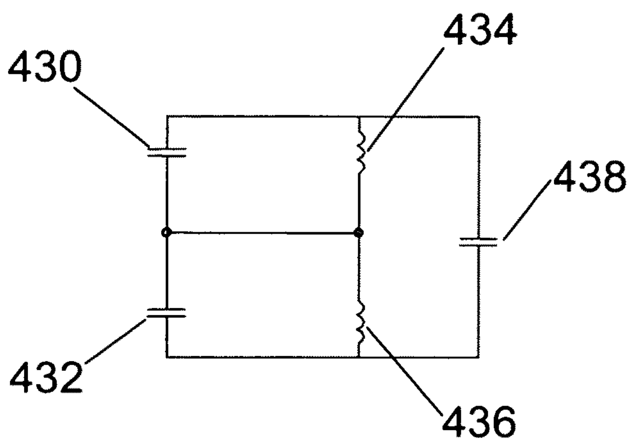

FIG. 24

500

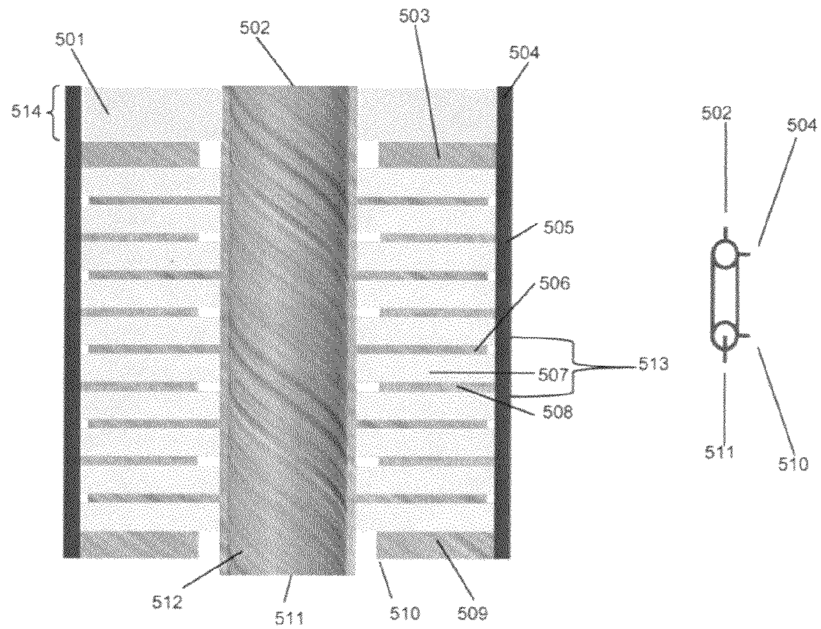
501
502
503
504
514
505
506
507
513
508
512
511
510
509
502
504
511
510

FIG. 25

BALUNS, A FINE BALANCE AND IMPEDANCE ADJUSTMENT MODULE, A MULTI-LAYER TRANSMISSION LINE, AND TRANSMISSION LINE NMR PROBES USING SAME

RELATED APPLICATIONS

This application is a continuation of prior U.S. patent application Ser. No. 12/313,385, filed Nov. 20, 2008, now U.S. Pat. No. 7,936,171, which claims benefit of and priority to U.S. Provisional Application Ser. No. 60/989,494 filed Nov. 21, 2007, both of which are incorporated by reference herein.

GOVERNMENT RIGHTS

This invention was made with U.S. Government support under Grant No. 5 R01 EB001035 by the National Institute of Health. The Government has certain rights in the subject invention.

FIELD OF THE INVENTION

This invention relates to improvements in baluns, and to balanced, high field, multi-resonant, fully transmission line, nuclear magnetic resonance (NMR) probes utilizing them, and to a fine balance and impedance adjustment module and a multi-layer transmission line used in NMR probes.

BACKGROUND OF THE INVENTION

Baluns are circuit elements that provide balance-unbalance transformation and suppress common mode currents. Existing baluns are complicated, work for only one or two closely related channels, and are rarely efficient at high power. Existing baluns are of several types and have a variety of drawbacks.

Baluns consisting of discrete transmission lines, such as (a) The Quarter Wavelength Sleeve Balun [1. Y. L. Chow, K. F. Tsang, C. N. Wong, An Accurate Method To Measure The Antenna Impedance of A Portable Radio, Microwave and Optical Technology Letters, Volume 23 Issue 6, Pages 349-352, 1999], (b) The Half-Wavelength Balun [2. Modern Antenna Design, Second Edition, Thomas A. Milligan, ISBN10: 0471457760, John Wiley, 2005], and (c) the Marchand balun [RF Design Guides: Systems, Circuits and Equations, Peter Vizmuller, ISBN: 0-089006-754-6, Artech House, Inc., 1995; Rutkowski, T. Zieniutycz, W. Joachimowski, K. Gdansk Div., Wideband Coaxial Balun For Antenna Application, Microwaves and Radar, 1998. MIKON '98., 12th International Conference on, Volume 2, Pages 389-392, ISBN: 83-906662-0-0, 1998], are bulky and long, and are difficult to build and adjust because they require precise machining.

Transformer type baluns that contain ferrite cores or beads [Onizuka Masahiro, Sato Kouki, Balun Transformer Core Material, Balun Transformer Core and Balun Transformer, U.S. Pat. No. 6,217,790, 2001] are lossy, not suitable for very high power, and not suitable in magnetic fields (as in NMR and MRI). They are also subject to heating problems, saturation problems and stray couplings.

The air-core transformer type balun [Weiss Michel, Martinache Laurent, Gonella Olivier, Multifrequency Power Circuit and Probe and Spectrometer Comprising Such A Circuit,

U.S. Pat. No. 7,135,866, 2006], needs precise alignment, is dependent on the resonance tuning of peripheral parts, and is subject to stray coupling.

Ferrite choke type baluns [Werlau Glenn, High Power Wideband Balun And Power Combiner/Divider Incorporating Such A Balun, U.S. Pat. No. 6,750,752, 2004] are lossy, not suitable for very high power, not suitable in magnetic fields (as in NMR and MRI) and subject to heating problems.

Air-core choke baluns [Burl Michael, Chmielewski Thomas, Braum William O., Multi-Channel Balun For Magnetic Resonance Apparatus, U.S. Pat. No. 6,320,385, 2001; Harrison William H., Arakawa Mitsuaki, Mccarten Barry M., RF Coil Coupling For MRI With Tuned RF Rejection Circuit Using Coax Shield Choke, U.S. Pat. No. 4,682,125, 1987] require an excessively large bending radius in the thick transmission lines required to handle very high power.

Transistor circuit baluns [Lee Young Jae, Yu Hyun Kyu, Active Balun Device, U.S. Pat. No. 7,420,423, 2008] are lossy, temperature sensitive, noisy and not suitable for high power applications.

Stripe line baluns, made from printed circuit board or laminate, [Niu Dow-chih, Chang Chi-yang, Lin Lih-shiang, Balun-Transformer, U.S. Pat. No. 6,531,943], are lossy, fragile, temperature sensitive, and not suitable for high power applications.

The dual band balun, comprising discrete transmission lines which can balance two working frequencies, [Clemens Icheln, Joonas Krogerus, and Pertti Vainikainen, Use of Balun Chokes in Small-Antenna Radiation Measurements, IEEE Transactions on Instrumentation and Measurement, Vol. 53, No. 2, pp. 498-506, 2004] has a mechanical tuning low pass filter that needs precise machining. Balancing the higher frequency requires changing the length of the balun. Furthermore, the two frequencies are closely related and cannot be adjusted independently. All of the above are incorporated by reference herein.

In some application such as communication antennas (including radio, television, wireless, and cell), common mode currents cause power loss, noise pick-up, and safety hazards. Baluns can improve efficiency and safety by suppressing the common mode currents. Multi-frequency baluns would allow antennas and other devices to operate efficiently and safely at multiple frequencies.

Nuclear magnetic resonance (NMR) spectroscopy (including magnetic resonance imaging—MRI) detects radio-frequency (RF) transitions between nuclear spin states. This requires delivery and detection of radio-frequency radiation by a coil around the sample. For multi-nuclear magnetic resonance, the coil must operate at multiple, disparate frequencies. And, to work well, it must be balanced at all these frequencies.

Sample coil imbalance reduces the homogeneity of the radiation, and thereby reduces excitation efficiency. Sample coil imbalance also causes signal loss and noise pick-up, resulting in poor signal-to-noise ratio. At high power, such as is required in solid state NMR, sample coil imbalance increases sample heating and arcing. Sample coil imbalance also compromises tuning and matching for salty or high dielectric samples. All of these effects of coil imbalance are greatly exacerbated at the high fields preferred in modern magnetic resonance spectroscopy.

Existing balanced NMR probes are either not fully transmission line or are balanced over only a narrow frequency range. By avoiding lump circuit elements, fully transmission line magnetic resonance probes achieve high efficiencies, reduced cross-talk between channels, and robust operation across a wide range of temperatures. Fully transmission line probes have the further advantages that (a) all the controls are in the bottom box which is outside the magnet and therefore accessible and always at room temperature, and (b) improved isolation between channels is possible through the design of common null points. However, in these probes, it is difficult to balance multiple channels at significantly different frequencies. A further challenge is conforming a fully transmission line probe to the dimensions of the NMR magnet and the associated facility, while maintaining balance, impedance matching and efficiency, especially over a multi-band (multi-frequency) operating range.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide improvements in baluns which allow for improved fully transmission line NMR probes in which the sample coil can be balanced at all operating frequencies.

It is a further object of this invention to provide such improvements in the probe transmission lines featuring common null points to improve channel isolation and segmented transmission lines to improve transmission efficiency.

It is a further object of this invention to provide such improvements including three robust, efficient, high power baluns including:

a clusterable pseudo-Marchand balun which is easy to build, suitable for applications across a wide range of temperatures, and capable of full balance for one channel,

a multi-band compound balun which is more compact, also suitable for applications across a wide range of temperatures, and capable of full balance across three or more channels,

and a tunable multi-band coaxial balun which is the most compact, the easiest to build, and capable of full balance across three channels.

It is a further object of this invention to provide such improvements in which the compactness of the compound balun and tunable coaxial balun make them especially suitable for applications in narrow bore magnets and facilities with low ceilings.

It is a further object of this invention to provide baluns which enable NMR probes which can be sized to meet magnet and facility structure constraints and yet be balanced, impedance matched and efficient over a number of operating frequencies.

The invention results from the realization that improved baluns which can be balanced at all operating frequencies can be achieved in clusterable pseudo-Marchand baluns, multi-resonant compound baluns and multi-resonant tunable coaxial baluns, and that such improved baluns are uniquely suited to implement fully transmission line NMR probes in which the sample coil will be balanced at all operating frequencies and the further realization that balance and transmission efficiency can be further improved by using a fine balance and impedance adjustment module.

The subject invention, however, in other embodiments, need not achieve all these objectives and the claims hereof should not be limited to structures or methods capable of achieving these objectives.

This invention features an improved Marchand balun including a first defined length transmission line having a center conductor and a shield, and a second transmission line having a center conductor and a shield. One end of the center conductors provides a balanced output/input; the other end of the second transmission line center conductor provides the unbalanced input/output. The shield of each transmission line is connected to ground and a capacitor is interconnected between the other end of the first defined length transmission line and ground.

In preferred embodiments the defined wavelength transmission line may be less than ¼ wavelength. The defined wavelength transmission line may have a length greater than

$$\left(\frac{n}{2}\right)\lambda$$

and less than

$$\left(\frac{1}{4}+\frac{n}{2}\right)\lambda$$

where n is a whole number. There may be an in-line filter at the balanced output of said second transmission line.

This invention also features a compound balun including a transmission line system having a center conductor and at least three concentric shields forming a first transmission line between the center conductor and the first shield, a second transmission line between the first and second shields, and a third transmission line between the second and third shields. The first transmission line receiving unbalanced input/output has at least three multi-band frequency signals at one end and provides a multi-band balanced output/input at the other. The second and third transmission lines form a choke to suppress the common mode current in the shield of the first transmission line at high frequency.

In preferred embodiments there may be a fourth concentric shield forming a fourth transmission line between the third and fourth shields. There may be a first reactive load between the second and third transmission lines. The first reactive load may include first and second sections spaced from each other about the periphery of the second and third shields. The first and second sections may include a reactive transmission line having one end of its center conductor connected to one of the second and third shields and one end of its shield connected to the other of the second and third shields. The other ends of the reactive transmission line's shield and center conductor may be connected to a capacitor for adjusting the choke for middle and low frequencies, respectively. There may be a second reactive load between the third and fourth transmission lines. The second reactive load may include third and fourth sections spaced from each other about the periphery of the third and fourth shields. The third and fourth sections may include a reactive transmission line having one end of its center conductor connected to one of the third and fourth shields and one end of its shield connected to the other of the third and fourth shields. The other ends of the reactive transmission line's shield and center conductor may be connected to a capacitor for adapting the choke for low frequency. The space between the second and third shields may include a dielectric member. The space between the first and second shields may include a static dielectric member and a moveable dielectric member movable toward and away from the static dielectric member for adjusting the suppression of the common mode current at the highest frequency loads.

This invention further features a tunable multi-resonant coaxial balun including a segmented main transmission line having an unbalanced input at one end and one of the balanced output terminals at the other. There is an adjustable transmission line having an inner conductor and shield with at least one dielectric member movable to and fro longitudinally between the inner conductor and shield for defining at least two adjustable transmission lines sections and adjusting the dielectric constant thereof for varying the output impedance of the adjustable transmission line to match the output impedance of the main transmission line at high frequency.

In preferred embodiments there may be a number, n, of the dielectric members defining a number, up to n+1, of adjustable transmission line sections. There may be a first and second capacitor at the output ends of each transmission line and/or a third capacitor connected between the input end of the adjustable transmission line and ground for adjusting the adjustable transmission line to match the output impedance of the segmented main transmission line at lower frequency when there are two channels. There may be a low frequency trap and either an impedance module or a low frequency module, connected respectively to the bottom or top of the tunable balance module, for adjusting the output terminal at the top of tunable balance module to match the output impedance of the segmented main transmission line (along with the first and/or second capacitor at the output ends of the segmented main, transmission line and adjustable transmission line) at the lowest frequency, when there are three channels.

This invention also features a multi-resonant pseudo-Marchand balun NMR probe including a base having at least one pseudo-Marchand balun, and a tuning and matching circuit associated with each pseudo-Marchand balun; and a probe body including a balanced pair of segmented main transmission lines at the proximate end interconnected with a sample coil at the distal end.

In preferred embodiments there may be in the base, common null point modules connected to each of the outputs of the at least one pseudo-Marchand balun. There may be in the probe body a fine balance and impedance adjustment module interconnected between the balanced pair of segmented main transmission lines and the sample coil. There may be a plurality of the pseudo-Marchand baluns and the pseudo-Marchand balun NMR probe may be multi-resonant. Each multi-resonant pseudo-Marchand balun may include a first defined length transmission line having a center conductor and a shield; and a second transmission line having a center conductor and a shield. One end of the center conductors may provide a balanced output/input. The other end of the second transmission line center conductor may provide the unbalanced input/output. The shield of each transmission line may be connected to ground and a capacitor may be interconnected between the other end of the first defined length transmission line and ground.

This invention further features a multi-resonant compound balun NMR probe including a base including at least one tuning and matching circuit and a probe body including a balanced pair of segmented main transmission lines interconnected to the at least one tuning and matching circuit, a multi-resonant compound balun connected to the main transmission line and a sample coil interconnected to the multi-resonant compound balun.

In a preferred embodiment the multi-resonant compound balun may include a transmission line system having a center conductor and at least three concentric shields forming a first transmission line between the center conductor and the first shield, a second transmission line between the first and second shields, and a third transmission line between the second and third shields. The first transmission line may receive unbalanced input/output at least three frequencies at one end and may provide a multi-band balanced output/input at the other. The second and third transmission lines may form a choke to suppress the common mode current in the shield of the first transmission line at high frequency. There may be in the base, a common null point module interconnected between the at least one tuning and matching circuit and the main transmission line. There may be in the probe body a fine balance and impedance adjustment module interconnected between the multi-resonant compound balun and the sample coil.

The invention further features a multi-resonant compound balun NMR probe having a base including at least one tuning and matching circuit, and a multi-resonant compound balun interconnected therewith. There is a probe body including a balanced pair of segmented main transmission lines at the proximate end and a sample coil at the distal end.

In preferred embodiments there may be a common null point module interconnected between the at least one tuning and matching circuit and the multi-resonant compound balun. There may be a transmission line extension in series between the common point module and the multi-resonant compound balun. There may be a fine balance and impedance adjustment module interconnected between the sample coil and the main transmission line. The multi-resonant compound balun may include a transmission line system having a center conductor and at least three concentric shields forming a first transmission line between the center conductor and the first shield, a second transmission line between the first and second shields, and a third transmission line between the second and third shields. The first transmission line may receive multi-band unbalanced input/output at one end and provide balanced output/input at least three frequencies at the other end. The second and third transmission lines may form a choke to suppress the common mode current in the shield of the first transmission line at high frequency.

This invention further features a multi-resonant tunable coaxial balun NMR probe having a base including at least one tuning and matching circuit and a probe body having a multi-resonant tunable coaxial balun connected to the at least one tuning and matching circuit at the proximate end and a sample coil at the distal end.

In preferred embodiment the multi-resonant tunable coaxial balun may include a segmented main transmission line having an unbalanced input at one end and one of the balanced output terminals at the other. There may be an adjustable transmission line having an inner conductor and shield with at least one dielectric member movable to and fro longitudinally between the inner conductor and shield for defining at least two balun transmission line sections and adjusting the dielectric constant thereof for varying the output impedance of the balun transmission line to match the output impedance of the main transmission line at high frequency. There may be in the base a common null point module interconnected between the at least one of the tuning and matching circuits and the multi-resonant tunable coaxial balun.

The invention also features a fine balance and impedance adjustment module including a pair of transmission line sections having the same or different characteristic impedances and having their shields connected together, a dielectric medium in each shield, a center conductor passing through the dielectric medium and snugly fit therein to permit movement and repositioning of the center conductor relative to the shields for adjustment of high frequency impedance and balance and a capacitor connected to each center conductor for adjusting lower frequency impedances and balances.

In a preferred embodiment the capacitors may be unequal. The capacitors may be variable.

The invention also features a multi-layer transmission line including an inner metal sleeve, an outer metal sleeve and a longitudinally aligned stack of metal (normally copper) disks that alternately make contact with the inner or outer sleeve of the transmission line, and are separated by dielectric material that makes contact with both sleeves.

In a preferred embodiment there may be a top coaxial transmission line section. There may also be an adjustable dielectric, which can be moved into and out of the top coaxial transmission line section to accomplish the fine adjustment of the electrical length.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Other objects, features and advantages will occur to those skilled in the art from the following description of a preferred embodiment and the accompanying drawings, in which:

FIG. **1** is an electrical schematic view of a pseudo-Marchand balun according to this invention;

FIG. **2** is a mechanical diagrammatic plan view of the pseudo-Marchand balun of FIG. **1**;

FIG. **3** is an electrical schematic view of a compound balun according to this invention;

FIG. **4** is a mechanical diagrammatic cross-sectional elevational view of the balun of FIG. **3**;

FIG. **4**A is a schematic plan view of the balun of FIG. **4**;

FIG. **5** is an electrical schematic view of a tunable multi-band coaxial balun according to this invention;

FIG. **6** is a mechanical diagrammatic cross-section elevational view of the dual frequency version of the balun of FIG. **5**;

FIG. **7** is a schematic block diagram of an HXY triple resonance NMR system which can utilize the probes of FIGS. **8-11**;

FIG. **8** is an electrical schematic diagram of a multi-resonant, clustered, pseudo-Marchand balun NMR probe according to this invention;

FIG. **9** is an electrical schematic diagram of a multi-resonant, compound balun NMR probe according to this invention with the compound balun near the tuning and matching modules;

FIG. **10** is an electrical schematic diagram of a multi-resonant, compound balun NMR probe according to this invention with the compound balun near the sample coil;

FIG. **11** is an electrical schematic diagram of a multi-resonant, tunable coaxial balun NMR probe according to this invention;

FIG. **12** is an electrical schematic view of a fine balance and impedance adjustment module according to this invention;

FIG. **13** is a mechanical diagrammatic cross-sectional elevational view of the fine balance and impedance adjustment module of FIG. **12**;

FIGS. **14** and **15** are top plan views of the module in FIG. **13** showing two different approaches to obtain a snug fit between center conductor and shield;

FIG. **16** illustrates reactance transformation curves of transmission lines;

FIG. **17** is an electrical schematic diagram of a segmented transmission line;

FIG. **18** illustrates reactance transformation in the shortening procedure based on FIG. **17**;

FIG. **19** illustrates reactance transformation in the lengthening procedure based on FIG. **17**;

FIG. **20** is a mechanical diagrammatic cross-sectional elevational view of a pair of segmented transmission lines as in FIG. **17**;

FIG. **21** is an electrical schematic view of an in-line filter;

FIG. **22** is an electrical schematic view of a common null point module;

FIGS. **23** and **24** are electrical schematic views of common null point modules for four and five operating frequencies, respectively, and

FIG. **25** is a multi-layer transmission line.

DETAILED DESCRIPTION OF THE INVENTION

Aside from the preferred embodiment or embodiments disclosed below, this invention is capable of other embodiments and of being practiced or being carried out in various ways. Thus, it is to be understood that the invention is not limited in its application to the details of construction and the arrangements of components set forth in the following description or illustrated in the drawings. If only one embodiment is described herein, the claims hereof are not to be limited to that embodiment. Moreover, the claims hereof are not to be read restrictively unless there is clear and convincing evidence manifesting a certain exclusion, restriction, or disclaimer.

There is shown in FIGS. **1** and **2** an improved Marchand balun also referred to as a pseudo-Marchand balun **10** which in this embodiment includes a first transmission line **12** with a length of less than ¼ wavelengths and a second transmission line **14**. The first transmission line **12** is of a length greater than

$$\left(\frac{n}{2}\right)\lambda$$

and less than

$$\left(\frac{1}{4}+\frac{n}{2}\right)\lambda,$$

where n is a whole number, including zero, and λ is wavelength. The shields **16** and **18** of transmission lines **12** and **14**, respectively, are connected to ground **19** through lines **20**. The center conductor **22** of transmission line **12** is connected to a capacitor **24** which may be a variable capacitor and has a capacitance which matches the impedance of the load. For example, for a load of 5 ohms at a frequency of 500 MHz, capacitance **24** may be approximately 1.5 pF. Center conductor **26** on transmission line **14** receives the unbalanced input and the balanced output occurs on center conductors **22** and **26**. Although as shown the input is unbalanced and the output is balanced, the balun works as well having a balanced input at center conductors **22** and **26** with the unbalanced output appearing at center conductor **26**. An in-line filter **28** may be provided to improve isolation between the improved Marchand baluns when multiple channels each require one. Typically it would be added to the channel with the poorest noise characteristic and positioned nearest to the common null point module which will be explained later with reference to FIGS. **22-24**. The length of transmission line **12** or the capacitance of capacitor **24** can be adjusted for any given transmission line **14** in such a way that the reactance at the output ends of transmission lines **12** and **14** have the same amplitude (equal to half of the magnitude of the load impedance) but opposite in sign. Changing the length of transmission line **12** provides coarse adjustment and changing the capacitance of capacitor **24** provides fine adjustment. The transmission lines are typically about 100 mm in length and about 29 mm in diameter at a frequency of 500 MHz. Since the output currents i**1** and i**2** are then the same, the potentials v**1** and v**2** at the output ends of transmission lines **12** and **14** should also be of equal amplitude but opposite sign. The unbalanced input has thus been converted to balanced output or conversely. When several channels with different working frequencies are connected to the same load, it is necessary to keep them isolated. In that case, the load impedance is adjusted to be approximately zero (that is, a null point) at the connecting point for the various channels, as will appear subsequently in the discussion of FIGS. **8**, **9**, **10**, **11** and **22-24**.

Another improved balun, a multi-resonant compound balun **40**, is shown in FIGS. **3** and **4**, including a center conductor **42** and at least three sleeves or shields **44**, **46**, and **48**, in fact a fourth sleeve or shield **50** is also shown in the embodiment of FIGS. **3** and **4**. Between sleeve **50** and sleeve **48** there is a dielectric **52** such as, for example Delrin, KelF, or PTFE. Between sleeves **48** and **46** there is typically air and between sleeves **46** and **44** there is air as well as one or more threaded dielectric rods, **56**, **57** which can be turned by the dielectric rod knobs **58** and **60**. There is a bottom or shorting plate **62** and accompanying each threaded dielectric rod **56** and **57** is a static dielectric member **64**, **66** and a sliding dielectric member **68** and **70** with threaded holes. Only two threaded dielectric rods with accompanying static and sliding dielectrics are shown; there may be more. Center conductor **42** is surrounded by a spacer **72** and an insulating sleeve **74**. Fixed chip capacitors **76**, **78**, and **80** and **82** not shown in FIG. **4** are mounted on top of balun **40**.

The inner surface of sleeve or shield **44** and the inner conductor **42** form transmission line **90**, which receives the unbalanced input at one end and provides balanced power at the other end. The outer surface of shield **44** and inner surface of sleeve **46** form transmission line **92**. The outer surface of shield **46** and the inner surface of shield **48** form transmission line **94** and the outer surface of shield **48** and the inner surface of shield **50** form transmission line **96**. Compound balun **40** is a multi-resonant or multi-frequency or multi-band device. The compound balun **40** is in the nature of a choking balun and it balances the output by suppressing the common mode current from flowing on the outer surface of the outer conductor or shield of transmission line **90**. This very large impedance between the outer surface and ground is achieved independently at each frequency by different approaches. There is a first reactive load **100**, FIG. **4**A between the second shield **46** and third shield **48** in the form of first and second sections **102**, **104** spaced from each other about the periphery of the second shield **46** and third shield **48** and spaced preferably as far apart around the periphery from each other as appropriate, for example, 180 degrees. There is a second reactive load **106**, between the third and fourth shields **48**, **50** in the form of third and fourth sections **108**, **110** also spaced from each other about the periphery of the third and fourth shields **48**, **50**. The peripheral spacing for both of these reactive loads should be far enough to prevent interference and can be as much as 180 degrees. Reactive section **102** includes a transmission line **120** whose center conductor **122** and shield **124** are connected between the second and third shields **46** and **48** at their inner ends and at their outer ends are connected to capacitor **126** in enclosure **127**. Similarly, reactive section **104** includes a transmission line **132** whose center conductor **130** and shield **128** are connected across second and third shields **46** and **48** at their inner ends and at their outer ends are connected to capacitor **134** in enclosure **136**. Similarly, with respect to reactive load **106**, reactive section **108** includes transmission line **140** whose shield and center conductor are connected at their inner ends between third and fourth shields **48** and **50** and at their outer ends are connected to capacitor **144** in enclosure **142**. Reactive section **110** likewise includes a transmission line **146** whose center conductor and shield are connected to shields **48** and **50** at their inner ends and at their outer ends are connected to capacitor **148** in enclosure **150**.

Choking at higher frequency is achieved by a quarter wave length resonator. Transmission line **92** is shorter than a quarter wave length with one end shorted by the bottom plate **62** and the other end grounded at the outer conductor. The dielectric in transmission line **92** comprises static pieces **64** and **66** and sliding pieces **68** and **70**. The choking frequency decreases with increasing length of these two pieces. Fine tuning is achieved by adjusting the relative positions of the two pieces with threaded dielectric rods **56** and **57**. The choking frequency will increase when the sliding pieces **68**, **70** are moved closer to the static pieces **64**, **66**. This tuning is not affected by tuning for the lower frequency because transmission line **120** and capacitor **126** form a notch or band pass filter for the higher frequency. The four capacitors **76**, **78**, **80** and **82** have low impedance at high frequency and the outside transmission lines, transmission lines **94** and **96** are bypassed at higher frequency.

Choking at lower frequency is achieved by a band stop filter. The high reactance required for the filter is developed in steps with remote impedance tuning devices formed by pairs of transmission lines and capacitors, one end of transmission line **96** is shorted by the top plate and the length is adjusted to obtain a small positive reactance at the open end. Transmission line **146** and capacitor **148** and transmission line **140** and capacitor **144** form remote impedance tuning devices adjusted so that transmission lines **146** and **140** have negative reactances where they connect to transmission line **96**. The parallel connections between transmission lines **96**, **146**, and **140** then forms a larger positive reactance after being transformed along transmission line **94**. This positive reactance increases further at the opening of transmission line **94** where transmission line **132** and capacitor **134** form another remote impedance tuning device adjusted to have a negative reactance where it connects to the open end of transmission line **94**. The band stop filter is then formed by connecting transmission line **94** and transmission line **132** in parallel with capacitors **76**, **78**, **80**, and **82** and transmission line **120**. Coarse tuning is accomplished by the choices of the capacitances **76**, **78**, **80**, and **82** while fine tuning is accomplished by adjustments of the capacitances **148**, **144**, and **134**. Reducing these capacitances increases the choking frequency. This tuning is not effected by tuning for the higher frequency because transmission line **120** and capacitor **126** have a very negative reactance at lower frequency and the positive reactance of transmission **92** at lower frequencies is negligible compared to the choking impedance. The values of capacitances **76**, **78**, **80**, **82**, **148**, **144**, **126**, and **134** are 3.3 pF, 3.3 pF. 3.3 pF, 3.3 pF, 21 pF, 21 pF, 3.2 pF and 4 pF, respectively, for a balun operating in the vicinity of 500 MHz, 125 MHz. The shield and center conductor are approximately 4 inches in length and shield **50** has a diameter of 3.5 inches, while shields **48**, **46** and **44** have diameters of 2.5, 1.25 and 0.375 inches respectively.

This compound balun can balance three channels without changing the configuration. The reactive section **110**, including transmission line **146** and capacitor **148**, is adjusted to form a notch or band pass filter for the middle frequency and transmission line **96** is bypassed at the middle frequency to keep the middle frequency channel balance isolated from the low frequency tuning. The band stop filter choking middle and low frequencies is then formed by connecting transmission line **94** and transmission line **132** in parallel with capacitors **76**, **78**, **80**, and **82** and transmission line **120**. Coarse tuning at the middle and low frequencies is accomplished by the choices of the capacitances **76**, **78**, **80**, and **82**. Then fine tuning at the middle and low frequencies is accomplished by adjustments of the capacitances **134** and **144**, respectively. Reducing these capacitances increases the choking frequency.

Analogously, adding an extra sleeve, three notch filters and one or more reactive sections outside the above three channel compound balun can make a compound balun capable of balancing four or more channels.

The third improved balun, multi-band tunable coaxial balun **160** shown in FIGS. **5** and **6** includes a segmented main transmission line **162**, as discussed in FIGS. **16-20**, and an adjustable transmission line (aTL) **164**.

Unbalanced input is provided at the center conductor **174** of the segmented main transmission line **162**. The other end of center conductor **174** is connected to capacitor **176** which provides one of the balanced output terminals at **178**. The center conductor **180** of the adjustable transmission line **164** is connected through capacitor **182** and low frequency trap **183** to ground **170**, when there are three channels. The other end of center conductor **180** is connected to capacitor **184** and constitutes the other balanced output terminal **186**. In FIG. **6**, the segmented main transmission line **162** and adjustable transmission line **164** are physically side by side, but particularly in FIG. **6** the main transmission line **162** is behind adjustable transmission line **164** which is shown in a cross sectional view. Center conductor **180** is surrounded by insulating sleeve **188**, a top spacer **190**, a bottom spacer **192**, and dielectric rod guide **194**. Threaded dielectric rods **196**, **198**, and **200** are received in spacer **192** and dielectric rod guide **194** and are moved to and fro, up and down in FIG. **6** by screw adjustment devices **202**, **204**, **206**, respectively, shown simply schematically. Insulating sleeve **188** is optional. It has two purposes: to avoid arcing or corona discharging at high power and to increase the dielectric constant of the aTL **164** so that its length can be reduced. If space is not an issue, the cross-section of aTL **164** can be expanded to reduce the risk of arcing and corona discharging and to raise efficiency.

To balance three frequencies, it is necessary to include the low frequency trap or band stop filter **183** and either the impedance module **185** or low frequency module **187**. Generalizations to more frequencies are analogous.

The low frequency trap or band stop filter **183** comprises capacitor **208** and inductor **209** connected in parallel. One end of **183** is grounded and the other end is connected to capacitor **182** at the bottom end of the tunable balance module **181**.

The impedance module **185** consists of transmission line **155** whose electrical length is around ¼ times the wavelength of the high frequency, and a middle frequency band-stop filter, connected in series. This middle frequency band stop filter comprises capacitor **157** and inductor **158** connected in parallel, and can also be in any circuit configuration having a high impedance at middle frequency and low impedance at high and low frequencies. One end of inner conductor **159** of transmission line **155** is connected to the ground through the middle frequency band-stop filter, and the other end is connected to the top of capacitor **182**.

The outer shields **166**, **168**, **156** and **156'** of transmission lines **162**, **164**, **155** and **155'** are grounded.

189 is a large capacitance capacitor which has low impedance at high and middle frequencies.

The low frequency module includes an impedance module **185'** which has the same structure as **185**. The top end of **185'** is connected through capacitor **189** to the top of capacitor **184** at the top end of tunable balance module **181**.

The ends **210**, **211** of the impedance module **185** and low frequency module **187** have high impedances at high and middle frequencies. At low frequency, the ends **210** and **211** have low inductive and capacitative impedances, respectively. These impedance differences keep the rest of the circuit from being affected by the impedance module **185** or low frequency module **187**, when there are three channels.

Capacitor **176** is the impedance matching capacitor for the middle frequency (and the low frequency when there are three channels) to improve the transmission efficiency.

With adjustment, the reactances at the output ends of capacitors **176** and **184** have the same amplitude (equal to half of the magnitude of the load impedance) but opposite in sign. Since the output currents **i1** and **i2**, are then the same, the potentials **v1** and **v2** at the output ends of capacitors **176** and **184** should also be of equal amplitude but opposite sign. The unbalanced input has thus been converted to balanced output. As for the previous baluns, the function of the balun can be reversed. That is the balanced output could be a balanced input and the unbalanced input could be an unbalanced output.

At high frequency, Capacitors **176**, **182**, **184** and **208** have negligible reactance. The aTL **164** behaves like a transmission line shorted at the bottom. The impedance is transformed along the transmission line to yield a negative reactance at the other end. The aTL **164** has a total length of ¼ to ⅜ times the wavelength of high frequency.

Referring again to FIGS. **5** and **6**, the actual length of the aTL **164** can be adjusted to accomplish coarse adjustments. That is, the longer **164**, the less negative the reactance above capacitor **184**. The fine adjustment is achieved by adding dielectric to **164** or removing it. Generally due to the dielectric members **192**, **194**, **190** and dielectric rods, there are “n” dielectric members resulting in “n+1” transmission line sections **191**, **193**, **195**, **197**, **199**. Dielectric is moved into or out of the aTL by turning the threaded dielectric rods **196**, **198**, **200**, see particularly FIG. **6**. When the dielectric is moved into **164**, the sections **191**, **193**, **195**, **197**, **199** with and without threaded dielectric rods inside become longer and shorter, respectively. As a result the electrical length of **164** is effectively increased and the reactance above capacitor **182** becomes less negative. The dielectric rod guide **194** can also be moved toward capacitor **184** to make the reactance above capacitor **184** less negative for fine adjustment.

At middle frequency, the adjustment of the aTL **164** is less effective in changing the reactance above capacitor **184**. Therefore we need to adjust capacitors **182** and/or **184**. The impedance above **184** becomes more capacitative when **182** or **184** is reduced.

For a dual band tunable coaxial balun, if the load has large impedance it is necessary to use both **182** and **184** to distribute the high voltage to avoid arcing. If the load has a medium or small impedance, either **182** or **184** alone suffices, but using both might reduce the standing wave ratio and thereby increase the efficiency.

At low frequency, there are two different choices.

If an impedance module **185** is connected to the top of **182**, the low frequency trap gives the top of **182** a high impedance at low frequency, so that the balance at low frequency is not affected by the adjustment of **182**. The impedance above **184** is adjusted with **184**, becoming more capacitative when capacitance of **184** is reduced.

If a low frequency module **187** is connected to the top of **184**, the low frequency trap gives the top of **184** a high impedance at low frequency, so that the balance at low frequency is not affected by the adjustment of tunable balance module **181**. The impedance above **187** is adjusted with **189**, becoming more capacitative when **189** is reduced.

The first case is easier to build and does not occupy any space around the output. But the second case has the advantage of totally independent tuning of the balance in all the channels.

When there are only two channels, the center conductor **180** of transmission line **164** is connected through capacitor **182** to ground **170**. None of impedance module **185**, low frequency module **187** and low frequency trap **183** is necessary anymore. The balances of the higher frequency and lower frequency channels are accomplished by following the above balancing principles and procedures for the high and middle frequencies of the three channel version.

With particular reference to FIG. **6**, tunable coaxial balun **160** can balance two frequencies such as 400 MHz and 100 MHz. The adjustable transmission line **164** may, for example, be 220 mm. Capacitor **176** is the impedance matching capacitor for lower frequency and in these ranges may have a capacitance of 76 pF. Capacitors **182** and **184** are the balance adjustment capacitors for lower frequency and may have a capacitance in this embodiment of 56 pF and 34 pF respectively.

One application of the baluns described in FIGS. **1-6** is, for example, in an NMR system **210**, FIG. **7**, although they can be used in many other applications as indicated in the Background. Such an NMR system **210**, FIG. **7**, employs a powerful magnet **212** into which is entered the probe body **214** of probe **216** which also includes base **218**. Base **218** may include, for example, three channel tuning/matching circuits, an H channel, an X channel and Y channel, for example. These are driven by respective H channel duplexer **220**, X channel duplexer **222** and Y channel duplexer **224**. Each of which in turn is driven by a power amplifier, again respectively, **226**, **228**, and **230**. Channel duplexers **220**, **222**, and **224** receive input from power amplifiers **226**, **228** and **230** to drive the tuning and matching circuits in the base **218** of probe **216**. Channel duplexers **220**, **222**, and **224** also provide an output to console **232** which processes the data received from probe **216** and delivers it to computer **234** with display **236** in a well known manner.

In further accordance with this invention the baluns of FIGS. **1-6** are employed in typically multi-resonant balun NMR probes. FIG. **8**, shows a multi-resonant, clustered, improved or pseudo-Marchand balun NMR probe **240**. In the base **218** of probe **216** there may be a number of channels **242***a*, **242***b*, **242***c*, . . . **242***n*, each including a pseudo-Marchand balun **10***a*, **10***b*, **10***c*, . . . **10***n*, and tuning and matching circuit **244***a*, **244***b*, **244***c*, . . . **244***n*. All of the pseudo-Marchand baluns **10***a*, **10***b*, **10***c* . . . **10***n*, connect to a common null point module **246**, as described in more detail with reference to FIGS. **22-24**, which is also in base **218**. One of the pseudo-Marchand baluns may include in-line filter **28***a* as referred to previously and described in more detail with reference to FIG. **21**. In-line filter **28***a* as previous explained functions to improve isolation and is usually placed as close to the common null point modules **246** as possible and associated with the nosiest channel. Probe body **214** of probe **240** includes a balanced pair of segmented main transmission lines **248**, at the proximate end of probe body **214**, described in more detail with reference to FIGS. **16-20**, and a fine balance and impedance adjustment module **250**, as explained in more detail with reference to FIGS. **12-15**. Attached to the fine balance and impedance adjustment module **250** at the distal end of probe body **214** is sample coil **252**. Each channel **242***a*, **242***b*, **242***c*, . . . **242***n*, is tuned to its working frequency, such as 500 MHz, 125 MHz, 50 MHz and matched to 50 ohms by its tuning and matching capacitor in the tuning and matching circuit **244***a-n*. The unbalanced RF input to each channel is converted by the pseudo-Marchand baluns **10***a-n* and transmitted through the common null point modules **246**, balanced pair of segmented main transmission lines **248**, and fine balance and impedance adjustment module **250**, to the sample coil **252** with balanced voltage. That is, with the potentials of both ends V_left and V_right, that have the same magnitude and opposite phases. The sample coil **252** delivers the RF energy to the sample and picks up RF signals emitted by the sample. The latter are transmitted through the fine balance and impedance adjustment module **250**, balanced pair of segmented main transmission lines **248**, and common null point modules **246**, to the baluns **10***a*-**10***n*, which reconvert them and send them on to the duplexers **220**, **222**, **224**, FIG. **7**.

In another NMR probe according to this invention, multi-resonant compound balun NMR probe **260**, FIG. **9**, multi-frequency compound balun **240** is disposed in base **218** near the tuning and matching modules **242***a*, **242***b* and **242***c*. Capacitors **262**, **264**, and **266** are tuning capacitors of channels **242***a*, **242***b*, and **242***c* shown in here in greater detail, also referred to as H channel, X channel and Y channel. Capacitors **268**, **270** and **272** are matching capacitors for the H, **242***a*, X, **242***b*, and Y, **242***c* channels. Tuning/matching branch transmission lines **274**, **276**, **278** are also provided for each channel. An in-line filter **28***a* may also be provided to improve isolation and may be placed within one of the channels, e.g. Y channel **242***c*. Also in base **218** is a transmission line extension **280** which can be used for adapting the impedance of the balun **240** to the common point module **246***a*. At the proximal end of probe body **214** is a balanced pair of segmented main transmission lines **248***a* which is interconnected with multi frequency compound balun **240** in base **218** and to fine balance and impedance adjustment module **250***a* in probe body **214**, which in turn is connected to sample coil **252***a* at the distal end of probe body **214**. Each channel **242***a*, **242***b*, **242***c*, is tuned to its working frequency, e.g. 500 MHz, 125 MHz, 50 MHz and matched to 50 ohms by its tuning capacitor **262**, **264**, **266** and matching capacitor **268**, **270**, **272**, all respectively. The unbalanced RF input to each channel is transmitted through common null point module **246***a* and transmission line extension **280**, if it is used, to compound balun **240** which provides a balanced output to a balanced pair of segmented main transmission lines **248***a*, then through fine balance and impedance adjustment module **250***a* to sample coil **252***a*, so that the sample coil **250***a* is supplied with balanced voltage. That is, with potentials at both ends v_left and v_right that have the same magnitude and opposite phases. The sample coil **252***a* delivers the RF energy to the sample and picks up RF signals emitted by the sample. The latter are transmitted back through the fine balance and impedance adjustment module **250***a*, and a balanced pair of segmented main transmission lines **248***a* to balun **240** which converts it and sends it to duplexers **220**, **222**, **224**, FIG. **7**.

The multi-resonant compound balun NMR probe **260** of FIG. **9**, disposes the compound balun near the tuning and matching modules in base **218**. In FIG. **10**, the multi-resonant compound balun NMR probe **290** disposes the compound balun **240** near the sample coil **252***a* in probe body **214** of probe **216**. Balun **240** is connected through a balanced pair of segmented main transmission lines **292** to common null point module **246***a* in base **218** which is connected to channels **242***a*, **242***b*, **242***c*, which are constructed in the same general manner as previously explained with respect to FIG. **9**. Again here, the in-line filter **28***a* is optional but helps to improve the isolation of the channels. Each channel **242***a, b, c*, is tuned to its working frequency such as 500 MHz, 125 MHz, 50 MHz and matched to 50 ohms by its tuning capacitors **262**, **264**, **266** and matching capacitors **268**, **270**, **272**. The unbalanced RF input to each channel is transmitted through the common null point module **246***a* and main transmission line **292** to compound balun **240** which converts it and supplies a balanced voltage to the sample coil **252***a* through the fine balance and impedance adjustment module **250***a*. That is, the potentials at both ends v_left and v_right have the same magnitude and opposite phases. Sample coil **252***a* delivers the RF energy to the sample and picks up RF signals emitted by the sample. The latter are reconverted by balun **240** and transmitted through the main transmission line **292** and common null point module **246***a* to duplexers, **220**, **222**, **224** shown in FIG. **7**.

Another multi-resonant NMR probe **300** is shown in FIG. **11**, where tunable coaxial balun **160** is disposed at the proximal end of probe body **214** and connects to sample coil **252***a* at the distal end. Tunable coaxial balun **160** is connected to common null point module **246***a* in base **218** which is connected to channels **242***a, b*, and *c*. Again each channel **242***a, b*, and *c* is tuned to its working frequency such as 400 MHz, 100 MHz, 40 MHz and matched to 50 ohms by its tuning capacitors **262**, **264**, **266** and matching capacitors **268**, **270**, **272**. The unbalanced RF input to each channel **242***a, b*, and *c* is transmitted through the common null point module **246***a* to tunable coaxial balun **160** to supply the sample coil **252***a* with balanced voltage. That is, with potentials at both ends v_left, v_right that have the same magnitude and opposite phases. Sample coil **252***a* delivers the RF energy to the sample and picks up the RF signal emitted by the sample. The latter is reconverted by balun **160** and transmitted through the transmission lines and common null point module **246***a* to the duplexers **220**, **222**, **224**, FIG. **7**.

The fine balance and impedance adjustment module **250** referred to in FIGS. **8-10** can serve two purposes. It can provide fine adjustment of the balance to compensate for physical imperfections of the load or stray couplings from the environment, and it can provide fine adjustment of the impedance to improve the RF power transmission efficiency. As shown in FIG. **12** it may consist of two transmission lines **310**, **312** with their center conductors connected to capacitors **314**, **316** and their shields **315**, **317** interconnected electrically and fixed together mechanically as shown by lines **318**. The transmission lines may be two very short thin transmission lines, for example, 10 millimeters in length with a diameter of ⅛ of an inch whose shields are connected together as previously explained or they may be short, thin, twin-axial transmission line. Adjustment is made by moving the joined shields **315**, **317** up and down along center conductors **319**, **321**. Capacitors **314**, **316** are chosen to provide the proper balance and impedance match. For example, at 500 MHz they may be in the range of 140 pF. They may be variable as shown in FIG. **13**. The center conductors **319** and **321**, FIGS. **13-14**, may be surrounded by dielectric filler **330**, **332** which contain holes **334**, **336** which snugly accommodate center conductors **319**, **321** so that as the joined shields **315**, **317**, fixed together, for example, at the solder joint **338**, move relative to center conductors **319**, **321** they may allow movement and repositioning of center conductors **319**, **321** and shields **315**, **317**. Alternatively, as shown in FIG. **15** with center conductor **319***a* being a plurality of strands having an eccentric cross section, the center conductor **319***a* may be rotated in the hole **334***a* to provide a sort of camming, locking action to hold the shield in its new position.

The balanced pair of segmented main transmission lines **248** may be made by connecting transmission lines with different characteristic impedances in series. In this way, a given impedance transformation can be achieved with different physical lengths. This is useful in systems with stringent length constraints, for example, NMR probes, in order to accommodate the particular dimensions of the machine and environment, while still achieving the desired impedance. There is shown in FIG. **16** the reactance transformation curves of three transmission lines **350**, **352**, and **354** whose characteristic impedances are $Z_0A>Z_0B>Z_0C$. To shorten a main transmission line, a segmented transmission line **248'**, FIG. **17**, may be made using three transmission line sections connected in series: a center transmission line **356** with characteristic impedance Z_0C, and two other equal transmission lines **358** and **360** at either end, with characteristic impedance Z_0E. Shortening is achieved with $Z_0E>Z_0C$, as shown in FIG. **18**: whereas a uniform transmission line alone needs to have a length AF, the 3-segment transmission line shown in FIG. **17** achieves this transformation with a significantly shorter length of AB+CD+EF. Lengthening is achieved with $Z_0E<Z_0C$, as shown in FIG. **19**: whereas a uniform transmission line alone needs to have the length AF, the 3-segment transmission line shown in FIG. **17** achieves this transformation with significantly longer length AB+CD+EF. The transformation principle is also applicable to combinations with just two sections of different characteristic impedances or with more than three sections. In NMR applications, medium or high characteristic impedance transmission lines are preferable to low characteristic impedance transmission lines because the former have less loss. FIG. **20** illustrates one example of a pair of segmented transmission lines **370**, **372**. Transmission line **372** has transmission line sections **374**, **376**, **378**, **380**, **382** which are defined by sliding dielectric sleeve **386"** and tapers **392**, **394**. The characteristic impedances of transmission line sections **374**, **376**, **378**, **380**, **382** are Z_0**382**>Z_0**374**>Z_0**380**=Z_0**376**>Z_0**378**. The sliding electric sleeve **386** is for the fine adjustment of the impedance transformation. Tapers **392**, **394** reduce the electric field strength at the connections between different sections to avoid arcing, corona discharging and breakdown.

The in-line filter referred in FIGS. **1**, **2**, **8-11** is shown in more detail in FIG. **21** where in-line filter **28'** includes a transmission line **400** including a shield **402** connected by lines **404** to ground **406** and center conductor **408** which is connected to capacitor **410**. Capacitor **410** and inner conductor or center conductor **408** are connected in series. At frequencies such as 50 MHz, one of the ends of the in-line filter may be at a null point, and both ends of the in-line filter have zero impedance. At other frequencies, such as 500 MHz, 125 MHz, in-line filter **28'** has a large impedance at the end connected to the null point and therefore filters out those frequencies.

Common null point module **246** referred to in FIGS. **8-11** is shown in more detail in FIG. **22**, as including a capacitor **420** and inductor **422**. The common null point module **246'** zeros the impedances at the operating frequencies, such as 500 MHz, 125 MHz, 50 MHz, so that channels will share the same null point. This improves the isolation between the channels resulting in improved efficiency and sensitivity. The fundamental unit of a common null point module is a combination of inductor **422** and capacitor **420**, or there may be a capacitor set including capacitor **420** and another capacitor **424** connected in parallel. Common null point modules for operating four frequencies, FIG. **23**, and up to five frequencies, FIG. **24**, include additional components. Common null point module **246"** for accommodating four operating frequencies includes two paralleled capacitor and inductor combinations **430** and **434**, **432** and **436**, connected in series. For five operating frequencies, common null point module **246'''**, FIG. **24**, includes two paralleled capacitor and inductor combinations **430** and **434**, **432** and **436**, connected in series, with an additional capacitor **438** connected to both ends in parallel.

Multi-layer transmission line **500** referred to in FIG. **25** can provide a long electrical length with significantly shorter physical length than a uniform transmission line, so as to conform to stringent spatial constraints. Although the RF transmission efficiency of a multi-layer transmission line is low, due to internal dielectric members, it is an effective and compact choice for choking circuits, such as transmission lines **92**, **94** and **96** in the present compound balun shown in FIGS. **3** and **4**; a short multi-layer choking transmission line permits a shorter RF power bearing transmission line which reduces RF transmission loss. Multi-layer transmission line **500** is also a compact and effective choice for the choking balun of high power RF circuit.

Multi-layer transmission line **500** incorporates a stack of metal (normally copper) disks that alternately make contact with the inner or outer sleeve of the transmission line, and are separated by dielectric material that makes contact with both sleeves. For example, metal disk **506** only contacts the outer surface of inner sleeve **512** and metal disk **508** only contacts the inner surface of outer sleeve **505**. Dielectric disk **507** contacts both the outer surface of inner sleeve **512** and the inner surface of outer sleeve **505**. Top disk **503** and bottom disk **509** only contact the inner surface of outer sleeve **505** and support metal disks and dielectric disks between them. Disks **506** and **508** with a dielectric disk **507** between them form a transmission line section **513** which is connected in series with neighbor similar transmission line sections. The top section **514** of this transmission line is a coaxial transmission line, formed by the inner surface of **505**, outer surface of **512** and adjustable dielectric member **501**, which is connected in series to the adjacent transmission line section.

All these sections, connected in series, constitute the multi-layer transmission line **500** of which 502 and 511 are the inner or center conductor nodes, while 504 and 510 are the outer conductor or shield nodes.

The dielectric material can be FR4, FR5, PTFE, KelF, Delrin or any other insulating material with small dielectric loss factor. The higher the dielectric constant of the dielectric, the longer the electrical length of the transmission line for a given physical length.

The greater the separation between disks **506** and **508**, the higher the characteristic impedance of transmission line section **513**.

Coarse adjustment of the electrical length can be achieved by adding or reducing the number of layers or transmission line sections, adjusting the separation between the metal disks, or changing the length of top section **514**. Fine adjustment is accomplished by moving the dielectric **501** into or out of the top section **514**. The electrical length increases as **501** is moved into **514**.

The physical length of a multi-layer transmission line with a given electrical length is several percent of the physical length of a uniform transmission line with the same electrical length. This shortening is more significant at low frequencies.

At 50 MHz, a ¼ wavelength (or 90°) multi-layer transmission line can be made with inner and outer sleeve diameters of around 8 mm and 25 mm respectively, a 40 mm long top section containing a sliding Delrin dielectric, and 95 sections with metal and dielectric disks in each layer made from commercial double-sided copper-clad printed circuit board (laminate) with thickness about 1 mm. The total physical length of the multi-layer transmission line is only about 135 mm while a uniform transmission line needs to be about 1500 mm to have this electrical length.

Although specific features of the invention are shown in some drawings and not in others, this is for convenience only as each feature may be combined with any or all of the other features in accordance with the invention. The words "including", "comprising", "having", and "with" as used herein are to be interpreted broadly and comprehensively and are not limited to any physical interconnection. Moreover, any embodiments disclosed in the subject application are not to be taken as the only possible embodiments.

In addition, any amendment presented during the prosecution of the patent application for this patent is not a disclaimer of any claim element presented in the application as filed: those skilled in the art cannot reasonably be expected to draft a claim that would literally encompass all possible equivalents, many equivalents will be unforeseeable at the time of the amendment and are beyond a fair interpretation of what is to be surrendered (if anything), the rationale underlying the amendment may bear no more than a tangential relation to many equivalents, and/or there are many other reasons the applicant can not be expected to describe certain insubstantial substitutes for any claim element amended.

Other embodiments will occur to those skilled in the art and are within the following claims.

What is claimed is:

1. A multi-resonant compound balun NMR probe comprising:

a base including at least one tuning and matching circuit; and

a probe body including a segmented main transmission line interconnected to said at least one tuning and matching circuit;

a multi-resonant compound balun connected to said main transmission line and a sample coil interconnected to said multi-resonant compound balun and wherein said multi-resonant compound balun includes a transmission line system having a center conductor and at least three concentric shields forming a first transmission line between said center conductor and said first shield, a second transmission line between said first and second shields, and a third transmission line between said second and third shields; said first transmission line receiving unbalanced input/output at least three frequencies at one end and providing a multi-band balanced output/input at the other; said second and third transmission lines forming a choke to suppress the common mode current in the shield of the first transmission line at high frequency.

2. The multi-resonant compound balun NMR probe of claim **1** further including in said base a common null point module interconnected between said at least one tuning and matching circuit and said main transmission line.

3. The multi-resonant compound balun NMR probe of claim **1** further including in said probe body a fine balance and impedance adjustment module interconnected between said multi-resonant compound balun and said sample coil.

4. A multi-resonant compound balun NMR probe comprising:

a base including at least one tuning and matching circuit; and a multi-resonant compound balun interconnected therewith;

a probe body including a balanced pair of segmented main transmission lines at the proximate end and a sample coil at the distal end and wherein said multi-resonant compound balun includes a transmission line system having a center conductor and at least three concentric shields forming a first transmission line between said center conductor and said first shield, a second transmission line between said first and second shields, and a third transmission line between said second and third shields; said first transmission line receiving multi-band unbalanced input/output at one end and providing balanced output/input at least three frequencies at the other end; said second and third transmission lines forming a choke to suppress the common mode current in the shield of the first transmission line at high frequency.

5. The multi-resonant compound balun NMR probe of claim **4** further including a common null point module interconnected between said at least one tuning and matching circuit and said multi-resonant compound balun.

6. The multi-resonant compound balun NMR probe of claim **5** further including a fine balance and impedance adjustment module interconnected between said sample coil and said main transmission line.

7. The multi-resonant compound balun NMR probe of claim **4** further including a transmission line extension in series between a common point module and said multi-resonant compound balun.

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